STRUCTURE AND TECTONIC HISTORY OF LEWISIAN GNEISS, ISLE OF BARRA
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STRUCTURE AND TECTONIC HISTORY OF LEWISIAN GNEISS,
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TEXT

being a thesis presented by

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ERRATA.

Page 77	line 15	"orogeny" should read "fold moveme
107	line 5	"orogeny" should read "deformation
125	line 15	"orogeny" should read "fold moveme
134	line 6	"recent" should read "late Lewisia
135	line 13	"orogeny" should read "deformation
149	line 4	"orogenies" should read "deformati
171	line 11	"orogenies" should read "deformati
204	line 4	"orogeny" should read "deformation
208	line 10	"orogeny" should read "fold moveme

CERTIFICATE

I certify that ALARIC M. HOPGOOD has been engaged in research for the equivalent of 14 full terms at the University of St. Andrews, that he has fulfilled the conditions of Ordinance No. 16, and that he is qualified to submit the accompanying thesis in application for the degree of Doctor of Philosophy.

DECLARATION

I certify that the following thesis is based on the results of research carried out by me, that it is my own composition, and that it has not previously been presented for a higher degree.

CAREER

In 1954 I obtained the degree of B.Sc. from Auckland University College, University of New Zealand and in 1956 completed the degree of M.Sc. with first class honours in geology. In 1956 I was awarded a Fulbright Travel Grant and spent the years 1956 to 1958 as a Teaching Assistant at the University of California, Berkeley.

In October 1958 I first matriculated at the University of St. Andrews and began research work on the structure of the Lewisian Gneisses of the Isle of Barra. In 1959 I was appointed to an Assistantship in the Department of Geology and in 1962 was appointed to a Lectureship.

Foliated gneiss, Bagh nan Clach.

C O N T E N T S

A B S T R A C T

The Lewisian of Barra has been found to comprise foliated orthogneisses ranging in composition from basic amphibolites, pyroxene and hornblende granulites and intermediate amphibole-bearing quartzo-feldspathic rocks to more acid gneisses of dioritic and granitic composition. It includes some inter-foliated acid rocks which may be paragneisses. The whole complex is cut by the Hebridean Thrust and the petrography of some strongly magnetic gneisses associated with the Thrust belt has also been described. The gneisses were intruded at an early stage by basic dykes, represented by rocks ranging from amphibolite to pyroxene granulite in composition. Cross-cutting relationships between Lewisian dykes and rectilinear quartzo-feldspathic pegmatite veins considered to have been injected along axial planes of folds are used to relate the phases of dyke intrusion and migmatization to the overall tectonic sequence.

Structural analysis has been carried out on planar and linear fabric data recorded on a base map on the scale of 1:10,560, from thin sections and also from the attitudes of structural elements recorded from selected localities in which the structure is particularly well exposed. Data recorded on the map have been considered separately from the following areas; the total area mapped; areas on each side of the main Thrust outcrop; areas exposing large scale structures; several small areas defined by an arbitrarily located grid to the west

of the main Thrust outcrop. From the results of the structural analysis and from consideration of structural relationships in the field a tectonic sequence has been determined.

The first recognizable event after the formation of the original banding was the development of isoclinal folding, followed by regional metamorphism in the amphibolite facies and succeeded in turn by the emplacement of basic to intermediate intrusions. Three successive phases of intrusion have been recognized here. Next, folding took place on axes now trending at 30°, followed by boudinage and agmatite formation and three further phases of basic intrusions. Part of the overthrust sheet exposed on the east coast was then subjected to regional metamorphism up to pyroxene granulite grade. Movement on the Hebridean thrust probably began soon after this, and asymmetrical folding about axes now plunging to 350° established the present general orientation of the foliation and produced axial planar traces which trend south-east. The gneisses were then folded about axes parallel to 150°, prior to strong folding about sub-horizontal axes trending at 100° which resulted in the present dominant fold pattern. Finally, very open folding took place about 60° trending axes. Except during the last fold period, migmatization was associated with all the folding and followed by pegmatite injection parallel to fold axial planes. Style has not been found to be a reliable guide to the chronological classification of folds. Open sigmoidal tension gashes related to the thrusting indicate that this movement continued after the final folding, and show the thrusting to have been directed to the west at an angle of elevation of between 5° and 10°.

A comparison has been made between the structure of this area and that discussed in some published work on the Lewisian elsewhere in the Outer Isles and the Scottish Mainland. The petrography and metamorphism of six phases of Lewisian dyke intrusives have been studied, and various possible mechanisms to account for dyke reorientation by shear have been examined in conjunction with the field relationships of these bodies. It is concluded that the intrusives have not been substantially reorientated with respect to the foliation since their emplacement.

A discussion is presented on the effects of anatexis on basic, intermediate and acid gneisses, on the emplacement of quartzo-feldspathic pegmatite veins, and on the formation of boudinage and agmatite. Three relative ages of pegmatites have been distinguished: early coarse quartzo-feldspathic pegmatites with dark feldspars, later pink quartzo-feldspathic pegmatites and late white quartzose pegmatites.

STRUCTURE AND TECTONIC HISTORY OF LEWISIAN GNEISS, ISLE OF BARRA.

I. INTRODUCTION

A. General

1. Topography and Climate

Little work has been done on the structure of the Archaean rocks of the Outer Hebrides, and the Isle of Barra was specifically selected as the site for the present research because it forms in itself a relatively compact unit of reasonable size which has not previously been investigated structurally. It also has the great advantage of possessing a long coastline, 55½ miles in all, which affords good exposure over much of its length, particularly in the north and north-west where spray from the Atlantic Ocean and wind blown sand have greatly inhibited the establishment of vegetation and soils on the glaciated rock surfaces. In the centre of the island much of the bedrock is obscured by peat, often several feet in thickness.

Any effect from the comparative mildness of the climate in the west due to the proximity of the waters of the Gulf Stream is largely offset by the severity of westerly gales which sweep the island throughout most of the year and which, besides limiting the growth of vegetation, at times reach forces sufficient to peel thin layers of peat from smooth rock surfaces exposed to the full force of the wind.

The Isle of Barra, excluding lochs, comprises approximately 21 square miles above high water mark, bounded by approximately 55.5 miles of rocky and sandy coast. It is the largest of the islands in the Parish making up the southern limit of the Outer Hebrides or "Long Island". The relief is only moderately steep, the greatest elevation being the summit of Heaval (1,260 ft.). Except for south-west facing cliffs, it is topographically similar to the other islands of the group of which it has been said that "no serrated outline, no spiry summits, no angles nor abrupt faces vary their appearance; one rounded and tame line separates them from the sky" (MacCulloch, 1819) (figs. I-1, 2, 3).

Due to the combined effect of extensive Pleistocene glaciation and present-day marine erosion, exposure of even the smallest-scale structures is excellent along the coast where mapping has been carried out in greatest detail. The quality of inland exposures is marred by the presence of lichen which conceals all but gross structural features, since the accentuation of foliation by differential weathering normally encountered in softer rocks is almost entirely absent in the gneiss. The formation of trenches rather than ridges along the lines of the post-Lewisian basic dykes further testifies to the extreme resistance to weathering and erosion of the Archaean country rock, little modified by subaerial erosion since glaciation.

The geomorphology of the coastline indicates that the area is one of submergence and it appears that the east coast is more strongly affected than the west, suggesting that slow eastward tilting is taking place. Some idea of the rate of submergence can be obtained from the fact that the small islet of Orosay (Norse, meaning high tide island) on the east coast, which is marked as an island at high tide only on the 1959 1:63.360 Ordnance Survey map (revised in 1956), is in fact isolated by a considerable depth of water even at low spring tides. In several places peat can be seen to dip below high water mark. The general grain of the country is controlled by a strongly developed east-trending series of more or less vertical joints, and in many cases the topography itself is a direct expression of the underlying structure. For example the gently north-dipping slopes at the northern end of the island are parallel to the foliation and the peninsulas of Ard Mhor and Ard Veenish are partially drowned strike ridges. The irregularity of the coastline is further increased by numbers of vertical walled slocs or geos formed by the marine erosion of joint blocks, fault breccia, and relatively easily weathered, regularly jointed, post-Archaean dykes. There are a few shallow fresh-water lochs on the island, most of which have been utilized as reservoirs for the water supply of the inhabitants. Streams are small and number no more than a half dozen.

Wind blown sand has produced fertile pasture (the Machair) along stretches of the north-east and west coasts at Eoligarry, Traigh Mhor, and Borve. The island's 1,500 odd inhabitants are nearly all crofters (apart from a very few fishermen and some small-traders).

With the exception of the recently restored Kiessimul Castle which is now in a good state of repair, archaeological remains are few and in poor condition, comprising in the main the remnants of chambered cairns and duns on hillocks and promontories on the west coast.

2. Geology

Apart from areas of Recent or sub-Recent windblown sands along the west coast, the island is composed almost entirely of a strongly deformed banded Archaean Lewisian Gneiss transected by sub-vertical unmetamorphosed basic dykes mostly of Tertiary age (Richey, 1948).

Foliation in the gneiss varies from laminae a few millimetres thick to bands of alternating acid and basic gneiss several feet in width. Generally, however, foliation is of the order of 5-10 centimetres wide. Close to zones of thrusting, the foliation tends to become obscure and finally, with brecciation and formation of pseudotachylite, disappears altogether. Evidence of mobilization after development of foliation (particularly in the acid rather than the basic gneiss) is seen in the presence of lenses and boudins of dark gneiss enclosed in coarse, banded quartzo-feldspathic rock, and in the injection of acid pegmatite veins into layers of basic rock.

In spite of MacCulloch's gloomy statement of 1819 (p. 81) to the effect that "The rocks of Barra offer nearly as little instruction to the geologist, as they display attractions to the lover of the landscape", it has been found during the present investigation that the Lewisian Gneiss here provides ample evidence of a long and interesting metamorphic history of great complexity.

While the exposure may be regarded as good by comparison with some areas on the mainland, it is on the average probably considerably less than 10 per cent of the total surface area and except for restricted areas close to the shore in the north-west it cannot compare in excellence with the exposure of the terrain in Greenland and Scandinavia, where much of the present-day structural investigation of Archaean gneisses is being pursued. Nevertheless, a considerable amount of structural data has been accumulated in the four years (1958-62) during which excursions amounting to a total of approximately 23 weeks were made to the island. (December 1958, February 1959, April 1959, Summer 1959, April 1960, Summer 1960, April 1961, April 1962, and September 1962).

B. Previous Work

Barra has received scant attention from geologists in the past, apart from the comprehensive survey examination carried out by Jehu and Craig (1923) in the early 1920's in the course of their investigation of the geology of the whole of the Outer Hebrides (Jehu & Craig 1923, 1925, 1926, 1927 and 1934). Prior to this, the most recent account of the geology of Barra, brief reference to the island was made by Donald Munro who visited it in 1549 (Jehu and Craig, 1923, p. 422; Martin, 1884). MacCulloch (1819) was the first writer to consider the geology of the island. He described in general terms the geology in his description of the Western Isles and noted the occurrence of the flinty crush-breccia. He mistook the associated ultramylonite for trap and he was puzzled therefore by the absence of any large "vein" of basalt in the neighbourhood. Heddle (Harvie-Brown and Buckley, 1888) mentions the island and remarks that it is part of an area of submergence. Geikie (1894), in common with MacCulloch (1819) and Heddle (Harvie-Brown and Buckley 1888), considered that the whole of the island had been covered by an ice sheet which had moved west-north-west (fig. I-4). He reported a scarcity of erratic material from the mainland and Inner Hebrides, although the present writer found Torridonian Sandstone and Cambrian Pipe Rock cobbles on most beaches and in the banks of drift above the beaches, as well as erratics of local gneiss farther inland (fig. I-5). Contrary to the statement of Jehu and Craig (1923, p. 422) raised beaches do occur, although rarely, and Quaternary conglomerates make up the remnants of a well defined, horizontally bedded, raised beach terrace standing between 10 and 12 feet above high water mark on the shore at the north-eastern end of the beach at Cliad (fig. I-6).

C. The Name Lewisian

Terminology relating to the rocks of the British Precambrian is confused and the literature abounds with examples of the inconsistent use of terms such as Group, Erathum, System, Series and Era, Period, Epoch, etc. The name Lewisian System was first proposed by Murchison in 1860 (Murchison 1860, p. 240) for the "Old or Fundamental Gneiss" of the north-west Highlands and Outer Isles. This name, synonymous with the affectionate but colloquial expression "The Old Boy" of the British Geological Survey, was used as an equivalent to the term "Laurentian" for rocks in North America considered to be of the same age.

Thus used, the name ranks as a second order chronostratigraphic unit (Report of the 21st Session, Norden, 1960, part XXV, International Geological Congress) and includes therefore all lithologies belonging to the Lewisian Period. As far as is known no new definition of the Lewisian has been proposed to supersede that put forward by Murchison (1860).

In the present work the term Lewisian (System) includes foliated gneisses, migmatites, quartzo-feldspathic pegmatites, as well as schistose rocks of the neighbouring islands of the Outer Hebrides and gneissose intrusives of Precambrian, and therefore presumably Lewisian age. On the Isle of Barra the only exposed representatives of the System are the Lewisian Gneisses which include all the above-mentioned lithologies with the exception of the schistose rocks.

D. General Petrographic Description

1. The Gneisses.

The petrography of Lewisian Gneisses from the Outer Hebrides has been described by several authors including MacCulloch (1819), Jehu & Craig (1923, 1925, 1926, 1927, 1934), Davidson (1943), Kursten (1957), and Dearnley (1962); but only Jehu & Craig (1923) have examined and described the rocks of the present field, the Isle of Barra. In their work on the Geology of the Outer Hebrides they distinguish orthogneisses, intrusions into the orthogneisses (also Archaean in age) and pseudotachylites with flinty crush-rocks. Included in the orthogneisses are descriptions of "hornblende rock", a dark ultrabasic rock which occurs in lenticles, primarily of hornblende with some magnesian pyroxene in the more acid gneisses. "Basic hornblende-gneisses" containing hornblende, garnet, pale green pyroxene and biotite are described as being enclosed in pale acid gneiss "in such a way as to suggest that the acid gneiss is relatively later". Pale pink to grey "acid gneisses" are described from various localities, notably from the north end of Barra and at Greian Head. These are made up of muscovite, biotite, strained quartz, microcline, oligoclase, zircon and magnetite, and are usually interbanded with folia of dark hornblende-gneiss and hornblende-biotite gneiss. "Banded gneisses" made up of acid gneiss interbanded with basic gneisses contain hornblende, andesine, a little quartz with apatite and iron ores as accessories. Only one example of garnetiferous orthogneiss is mentioned, that from the coast north-west of Ben Scurrival.

Under "Intrusions into the Orthogneiss" Jehu and Craig (1923) group "hornblende granulites", "pyroxene granulites" and cross cutting "pegmatites". The hornblende granulites are described as having a granular structure as a rule, although they are occasionally schistose, being rich in hornblende with subordinate pale green clinopyroxene, some quartz, and andesine, apatite, and in some cases minute garnets. They occur as dyke-like masses subparallel to the foliation of the gneisses. The pyroxene granulite bodies are less common than the hornblende granulites, are larger and tend to be subparallel to the foliation of the country rock as at Rudha Liath. In thin section these display granulitic structure and are seen to contain hornblende, both rhombic and monoclinic pyroxene, garnets, labradorite, iron ore (magnetite), and apatite. The pegmatites are considered by Jehu & Craig (1923) to be the latest members of the Archaean Complex: they contain purple feldspars, oligoclase with antiperthitic microcline, a little andesine, and quartz; microcline, some quartz, biotite, magnetite masses up to the size of an egg; albite-oligoclase, a little muscovite, quartz, biotite (diopside) and orthite.

In so far as the slightly differing lithologies seem to have little effect on the form of the folding (except in the case of the basic bands which have acted in a more competent fashion and have reacted differently to migmatisation) lithological descriptions are given in the present study only for the sake of completeness and not as factors fundamental to the study of the tectonic style. The greatest lithological effect is probably that due to basic gneiss bands which act as rigid "ribs", thus influencing the fold forms in their immediate vicinity.

Generally speaking the Lewisian Gneisses seen in the present investigation can be said to comprise combinations of the following types of gneisses: light coloured acid gneiss, dark green hornblende gneiss, dark grey hornblende-pyroxene gneiss and dark grey garnet-hornblende-pyroxene gneiss. All are foliated to some extent, exhibiting preferred orientation of their constituent minerals, and in the case of the more acid members the texture may approach that of augen gneiss.

There is little marked petrographic variety in the foliated gneisses, and the differences in lithology are due largely to slight variation in the relative proportions of the constituent minerals from one band to another. The overall mineralogy is simple: only occasionally is there a departure from the usual combination of about half a dozen species, and then only to the extent of little more than a trace of the additional mineral. The following is a list of the minerals determined in thin section, grouped under three broad divisions according to the relative abundance of grains in the thin sections examined (Table 1). The table is intended only as an indication of relative frequencies of occurrence of grains and is not based on a systematic quantitative investigation.

The composition of the plagioclase has been determined on a flat stage microscope using relative refractive index and maximum extinction angles as the means of identification (Rogers and Kerr 1942, p. 241). The metamorphic textural terms employed are those used by Harker (1956, pp. 200-202) and Berthelsen (1960, p. 24).

a) Acid Gneisses.

These, although light coloured as a rule, may become dark grey in colour with increase in content of magnetite. Thin section examination shows that they are composed almost entirely of feldspar, with a little quartz and irregular shreds and veins of magnetite disseminated throughout. Pleochroic green-brown to red-brown biotite is present in twisted shreds and laths in amount usually not exceeding 10 per cent. Rarely, a few grains of pleochroic green

Table 1. Frequency of occurrence of grains of different mineral species in the gneisses.

Common	Less common	Rare
Brown biotite	Epidote (granules)	Kyanite
Dark green-brown hornblende	Chlorite (pennine)	Pale blue-green hornblende
Apatite	Muscovite	Zircon
Clinopyroxene	Hypersthene	Colourless to pale-green clinopyroxene
Quartz	Scapolite	?Cummingtonite
Orthoclase	Garnet (including almandine)	Clinozoisite
Plagioclase (Oligoclase-andesine)	Microcline	Carbonate
		Haematite
Magnetite		Lilac mineral replacing biotite[1]

hornblende may be present. The plagioclase feldspar (oligoclase) is almost invariably twinned on the albite and pericline laws, is normally clouded with sericite and frequently exhibits undulose extinction. Orthoclase is associated with microcline and acid plagioclase in subequal amount, and commonly contains perthitic intergrowths. Clear pools and anhedral grains

[1] The following properties were determined for this mineral although it has not been possible to identify it; lilac to colourless; biaxial +ve; large 2V; birefringence about 0.008; refractive index close to biotite, (slightly above and below) and n 1.540; extinction Z length 3°-35°; length (parallel to biotite flakes) fast or slow; separate patches in same biotite crystal extinguish simultaneously and thus have the same optic orientation and extinction angle. Lilac cordierite referred to by Beavis (1961) and purple feldspars mentioned by Berthelsen (1960, p. 29) are faintly similar examples which have been noted in the literature on gneisses, although neither of these is very closely akin to the present occurrence.

of quartz exhibiting undulatory extinction are present in subordinate amount and apatite in subhedral to euhedral crystals, often as large as 2 millimetres in length, is a common accessory.

b) Hornblende gneisses.

In hand specimen these are dark, green to black rocks of medium grain-size.

In thin section it is seen that they comprise, on an average, 40 per cent to 60 per cent dark minerals, mostly subhedral, dark green pleochroic hornblende crystals with extinction angle $c \wedge Z$ ranging from 15° to 20°, 2V approximately 60° and negative optic sign. Twinning is sometimes present as thin seams with [100] as twin plane. Pleochroic red-brown biotite is occasionally present and small irregular flakes of magnetite are scattered throughout. Feldspar, clouded with sericite, and strained quartz together make up the bulk of the light minerals. Subhedral apatite crystals are ubiquitous. The feldspar is mostly microcline with perthitic intergrowths, although some with symmetrical extinction angles of 10° displaying polysynthetic twinning is close to oligoclase in composition. Occasionally myrmekite may be present and, in a few cases, minute flakes of haematite have been observed.

c) Hornblende-pyroxene gneisses.

Dark, grey-green in hand specimen, these rocks are in all other respects similar to the hornblende gneisses in appearance. Dark minerals make up 50 per cent of the rock and of these, pale green clinopyroxene constitutes approximately 50 per cent to 60 per cent.

The pyroxene is non-pleochroic pale green diopsidic augite, in granules showing prismatic cleavage, with a biaxial positive interference figure, and 2V about 60°. Extinction $c \wedge Z$ averages about 50°. With reduction in quantity of pyroxene, these rocks grade into hornblende gneisses.

d) Garnet-hornblende-pyroxene gneisses.

In some instances, very small, pink garnets are disseminated throughout the hornblende-pyroxene gneisses. As a rule these are greatly fractured and range in degree of crystallinity from anhedral to subhedral: normally they are just large enough to be distinguished in the hand specimen.

2) The Cataclastic Rocks.

Rocks produced during movement on the Hebridean Thrust belong to this category and include the flinty crush-breccia and pseudotachylite described by Jehu and Craig (1923).

a) Pseudotachylite.

In the field the pseudotachylite occurs as ramifying veins generally not exceeding a few inches in thickness (locally, however, it may form veins several feet wide) transecting the country rock in an irregular fashion and in such a way as to suggest that it was in a highly fluid state at the time of emplacement.

In thin section, the rock appears as a nearly opaque, dark brown, banded mesostasis enclosing minute angular mineral and rock chips aligned parallel to the banding. Because of its extreme opacity and fineness of grain, little has been learned from examination of oriented thin sections of this rock, and in none of the thin sections examined were spherulites seen, although these have been described previously by workers from other localities in the Outer Hebrides (Kursten, 1957).

b) Flinty crush-breccia.

Locally derived brecciated gneiss welded by dense cryptocrystalline pseudotachylite to form flinty crush-breccia occurs in belts of varying width within a few feet of, and parallel to, the thrust zones.

3) The Magnetic Gneisses.

The petrography of this particular group of gneisses was considered to be worthy of further attention in the hope that it might be possible to use it as a stratigraphical unit or marker in large scale structural mapping. It was hoped too, that provided the magnetism is confined to a particular lithology, it would be possible to map the magnetic gneisses which occur in various parts of the field using a dip circle or small magnetometer.

In the course of mapping the southern part of Barra it was discovered that the gneiss in several of the exposures is strongly magnetic, particularly in those areas closely associated with the main Heaval Thrust, and in many cases the magnetism is quite strong enough to reverse the direction of the needle of a compass completely when placed close to the outcrop. As field work progressed magnetic gneiss was found at other localities and these, as far as could be determined, were in every case either pseudotachylite veins or rock associated with thrusting and pseudotachylite veins. The veins are often very thin and sometimes only an inch or two wide.

Several specimens of magnetic gneiss were collected in order to attempt to determine whether or not there is any relationships between degree of magnetism and lithology. Thin sections were prepared of thirteen specimens collected from strongly magnetic exposures. These include both magnetic and non-magnetic rock of comparable lithologies as seen in hand specimen and point counts were made of the following minerals:- Opaques, quartz and feldspar, hornblende, biotite, apatite, pyroxene. The results are compiled in Table 2.

It will be seen that there is no convincing relationship between the degree of magnetism of any one specimen and its mineralogy. Specimens have been labelled simply "magnetic" and "non-magnetic" depending upon whether or not a hand specimen will cause a readily visible deflection of the needle of a Swiss "Meridian" compass.

More refined methods of testing do not appear to be warranted in the present research, particularly as the results obtained demonstrate fairly conclusively that mineralogy alone does not appear to be an important factor in the manifestation of magnetism. For this reason the rocks would be valueless as marker bands for structural mapping. A simple plot of magnetic and non-magnetic against percentage of opaque shows immediately the relationship between degree of magnetism and opaques.

What does emerge from this examination is the fact that there appears to be some sort of association between degree of magnetism and the development of pseudotachylite, since strong magnetic anomalies are almost invariably associated with areas of thrust tectonics, and in

Table 2. Modal compositions of magnetic and non-magnetic gneisses.

Specimen number	Magnetic (M)	Percentage Opaque	Opaque	Quartz and Feldspar	Hornblende	Biotite	Apatite	Pyroxene	Total
485	M	0	0 much opaque dust	2368	669	191	3	-	3261
487		.75	29 opaque dust grains on boundaries	3644	-	165	3	-	3841
482	M	2.7	106	3038	179	596	17	-	3956
484	M	2.5	99	3001	183	676	50	-	4009
486	M	0	1	1156	2101	5	-	542	3805
496	M	3.25	111	1722	1275	278	32	1	3419
497	M	2.4	104	2274	970	666	trace	298 Pt.	4312
498		0.89	42	2571	1300	794	33	-	4740
27		3.2	94	2792	3	28	1	9	2927
499		1.3	39	2686	-	258	4	-	2987
500	M	6.9	199	2565	107	-	8	-	2879
501	M	2.5	95	2525	368	761	44	1	3793
502		1.3	56	1740	1128	341	4	1041	4310

Pt. = Pseudotachylite

particular with rocks seamed by pseudotachylite veins. This suggests that the pseudotachylite at some time must have been at a temperature above the Curie Point of the dominant magnetic mineral (? magnetite) in order for the magnetism of the cooling rock to be induced by the earth's field. With refined methods, it might be possible to determine the age of the thrust period using the position of the magnetic pole as a basis for the determination.

Further investigation of this problem would almost certainly provide a fruitful research topic in its own right.

E. Acknowledgements

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II. NATURE OF THE RESEARCH

A. Purpose and Scope of the Investigation

1. Scope of the Investigation

An attempt has been made to determine the degree of homogeneity (Turner and Weiss, 1963, p. 16) of the area in terms of different measurable mesoscopic structures, to investigate the geometry of the rock fabric (Sander, 1930; Turner and Weiss, 1963, p. 19) as a whole, and to relate this to tectonic style (Turner and Weiss, 1963, p. 79). From consideration of the structural relationships between the subfabrics a tectonic sequence has been drawn up.

The investigation comprises:-

(1). Mapping to obtain a general picture of the structure of the Lewisian Gneiss. The scales used are:- 1:63,360 (1 inch to 1 mile), 1:25,000 ($2\frac{1}{2}$ inches to 1 mile), 1:10,560 (6 inches to 1 mile), 1:2,500 (25 inches to 1 mile) and 1:625 (100 inches to 1 mile).

(2). Examination of the megascopic fabric of the gneisses.

(3). Study and comparison of the microscopic fabric with the macroscopic fabric to see whether or not the microfabric of the grain orientation (particularly in minerals such as quartz and biotite) confirms any evidence for the latest period of deformation recorded in the megascopic fabric.

(4). Examination of the styles of different periods of deformation to see if these are distinctive, and consideration of their relation to conditions of deformation in so far as these can be determined.

(5). The determination of the relationship, if any, between the various episodes of folding and mobilisation of the gneisses and pegmatite injection.

(6). Mapping and examination of the Hebridean Thrust and its effect on the gneisses in an attempt to determine the age of the thrusting, and examination of the nature of the pseudotachylite and its magnetism.

(7). Examination of the relationship and comparative metamorphic grade of the Archaean basic intrusives, and comparison with basic dykes in the Lewisian Gneiss of so-called Scourian age in the north-west Highlands (Sutton and Watson, 1951).

(8). Consideration of the problem posed by the lack of reaction structures around minerals within gneisses transitional between amphibolites and pyroxene granulites, with which are associated metamorphosed dykes of both pyroxene granulite and amphibolite grade (see map I).

No attempt has been made to estimate the thickness of the gneisses, largely because the results of such an undertaking would almost certainly be meaningless in view of their highly deformed nature and the ubiquity of repetition of folia due to isoclinal folding and shearing. Secondly, and this factor is of more fundamental significance in the present investigation, the absolute thickness of the series is not important to the consideration of the geometry of the structure. From consideration of all the field evidence, certain factors emerge which indicate with reasonable certainty that a number of distinct episodes of deformation have been recorded in the fabric of the Lewisian Gneiss. Those episodes, for which there is considered to be fairly conclusive evidence, are listed as distinct phases and are discussed individually. (See page 40).

B. Method of Investigation

1. General

To the specialist in structural petrology, the unravelling of the structural history of the Lewisian Gneiss has presented a problem which, although challenging, has previously lacked appeal by virtue of its complexity. This is because such a structural investigation can rarely if ever produce a precise, clear-cut result and as such is unacceptable to the purist. In the present study it has been necessary to employ a variety of techniques in an attempt to obtain the clearest possible picture of the structure.

Prior to the preparation of field sheets and base maps, a preliminary examination was made of some of the better exposed areas and a reconnaissance made of the coast using topographic maps on the scale of 1:10,560. The immediate consequence of this survey was that the 1:10,560 topographic maps were found to be totally inadequate for the degree of accuracy required in the structural mapping necessary for the work. It was decided to use aerial photographs as field sheets for the following reasons. In order to obtain an accurate picture of the geometry of the structures in the gneisses it would be necessary to record and locate accurately thousands of measurements of both planar and linear features. On 1:10,560 topographic maps, devoid of all but the most prominent topographic features and lacking contours, the only possible means of location of each measurement on the map entailed resection using a compass. This operation would not have been possible everywhere on the island and even where feasible, would have entailed a tremendous amount of work and thus have taken an inordinate time to accomplish. On the other hand, the aerial photographs used were of indifferent quality and sometimes greatly distorted (most are labelled "unserviceable") and comprise several sorties. Measurements were made wherever possible on distinctively shaped rock exposures and this enabled rapid and accurate location in the field. It was possible to correct for distortion to some extent when transferring from these field sheets to the base maps. Some distortion of structure is inevitable, but this is not considered to be such as to seriously effect the structural interpretation since the continuity and relationships between measurements, and thus the essential geometrical features, are still preserved. Almost certainly the use of the topographic maps available instead of aerial photographs would have precluded the accurate mapping of all but the largest structures.

In nearly all cases the data used in the structural analyses were recorded on overlays on these aerial photographs which are on a scale of approximately 1:10,560. Exception was made to this rule in some areas where exposure and structure warranted more detailed investigation. In these cases aerial photographs enlarged to a scale of 1:2,500 were used as field sheets from which maps on the same scale were compiled. All the field sheets - tracing paper overlays on 1:10,560 aerial photographs - were ruled with lines at intervals of approximately one inch, parallel to magnetic north so that the strikes of all attitudes measured could be recorded immediately with correct orientation on the field sheets. From the field sheets, attitudes were transferred to a master map on the scale of 1:10,560. In one or two well exposed coastal tracts several measurements were recorded from very small areas and plotted separately. The plots obtained were used as additional evidence to confirm the nature of the structural geometry.

It soon became evident that in most parts of the island there is a decided lack of distinctive bands in the gneiss. Folia suitable as markers are neither sufficient in number nor continuous enough to permit of their use in mapping, and in any case exposures are not sufficiently large or continuous to enable lithological units to be used for mapping the form of large scale structures. An exception to this was found at the north end of the island at Bagh nan Clach near Scurrival where the exposure is extremely good, and in part of the area the occurrence of continuous amphibolite bands interposed between light coloured quartzo-feldspathic folia enabled litho-structural mapping to be carried out on the scale of 1:2,500. In the remainder of the Scurrival area the form of the structure was obtained from the use of form-lines, the trace of form-surfaces on the outcrop (McIntyre and Weiss, 1956, p. 149).

Detailed mapping and accurate tracing of form-lines has not been possible everywhere because of the quality of the exposure and in most cases the lines drawn on the map are approximations or diagrammatic. It will be appreciated that to obtain in this way an objective structural picture of rocks which show so little lithological variation, and whose structure is extremely complex, individual folia must be traced in the field foot by foot and their positions accurately located on the map. After seeing in detail the structure in those areas which are well exposed, it became clear that any representation of the structure obtained from intermittent exposures elsewhere must of necessity be a very simple generalization compared to the incredible complexity which must in fact exist. Some idea of this complexity will be obtained from the photographs accompanying the text (See for example fig. II-1). It should also be noted that, by contrast, many of the outcrop patterns which appear to represent folding of great complexity are due in fact to a combination of interference patterns and the attitude and form of the outcrop surface in relation to the structure in question. This effect has previously been discussed frequently in the literature (e.g. Reynolds and Holmes, 1954; Ramsay, 1962). Exceptionally fine examples of this effect can be seen south of Bagh nan Clach (fig. II-2) and at the north end of Bagh nan Clach, near Scurrival (fig. II-1), where the outcrop of thin quartzo-feldspathic folia in basic gneiss forms an intricate pattern. It was found possible to reproduce the form of the pattern of figure II-1 by slicing at a suitable angle a model folded in two directions at right angles (figs. XII-35, 36, 37). Several other "improbable" looking outcrop patterns, which at first sight suggest extensive thinning and lensing, can be accounted for simply by considering the position and attitude of the surface of the outcrop in relation to the structure (figs. II-3, 4).

Structural data for the statistical analyses were taken from the master map prepared from the aerial photographs and plotted for selected areas in lower hemisphere, equal area projection. It should be emphasised at this stage that the attitudes recorded are those considered to represent the average in the immediate vicinity of the spot chosen for measurement. Whenever possible, several readings were taken to obtain this value but more often, for the reasons stated below, it was impossible to follow this procedure, and therefore the danger was always present that a certain element of subjectivity may have influenced the measurement. It is often difficult to determine, other than very approximately, the exact dip of the foliation because the gneisses rarely weather out to form a three-dimensional outcrop. Generally one has to deal with an essentially smooth glaciated surface on which it is often difficult to determine even the sense of the dip, let alone its magnitude (fig. XII-4). For this reason the angles of dip are often recorded only to the nearest 5^{o}, but more usually 2^{o}, and although the effect of this sometimes shows as local grouping on the plots it was hoped that statistical analysis of a sufficiently large number of attitudes would overcome any inaccuracies arising from this. In any case it seemed at the outset that the very least likely to emerge from the investigation would be an indication of the general geometry and form of the structures present in the gneisses, and it was felt that continuation of the work was warranted on this basis alone. Nevertheless it is possible, and indeed probable, that further examination of the structure in selected well-exposed areas could well repay the time of the investigator and it is hoped to continue at a later date the study of the Lewisian gneisses in this and neighbouring parts of the Outer Hebrides.

During the initial general examination of the whole area (in particular along the coast) the general styles of the folding and their degree of regularity were noted, both in the broad scale and in the minor structures measured in the field. Later, a more detailed examination was made on a mesoscopic scale in selected well-exposed areas, in particular in the vicinity of Scurrival. Examination of the variation between mesoscopic fields extended the range of the investigation to the macroscopic scale and finally examination on a microscopic scale in the laboratory was carried out to complete the investigation. (See page 229).

Initially, after the decision was taken to use aerial photographs, it was intended that the whole of the island (and also the off-shore islands) would be arbitrarily subdivided into approximately equal areas of the size of a single aerial photograph. However, in view of the haphazard aerial coverage available (the island is covered by at least three flights on slightly differing scales none of which is parallel to either of the other two), and in order to reduce to a reasonable number the photographs required, it was decided to abandon the strict grid coverage and to transfer data from the photographs to a master outline map on a scale of 1:10,560 (map I). From this map a grid could be derived if necessary to which plotting could be related. Plots direct from information recorded on individual photographs, were prepared as a routine part of the investigation, nevertheless, although it has not been considered worth while to figure these here.

Following field mapping on 1:10,560 photographs and transference of the data to the master 1:10,560 map, form lines were drawn in as far as was possible from the attitudes measured on the available outcrops. Consideration of the resultant postulated macroscopic structures with the aid of the form of outcrop patterns shown on the aerial photographs in some areas indicated that mapping on enlarged 1:2,500 photographs would be rewarding. Apart from the well-exposed Scurrival area (map II), mapping on the scale 1:2,500 was carried out on the ground west of Castlebay at Rudha Glas (map III), on the hillside east of Tangusdale (map IV), at the east end of Halaman Bay (map V), on the hillside south-east of Tangusdale at The Croig (map VI) and on the small island of Fiary (map VII). Also, because attitudes on the map suggested the presence of interesting macroscopic structures in the area stretching from Castlebay north to Borve (map VIII), it was decided to grid this area arbitrarily on a small scale and plot the attitudes from each square individually in order to see if changes in structural trend would emerge.

One other area has been mapped in detail on a sketch map of approximately 1:625 scale. This encompasses the end of the small peninsular called Leenish, north of Brevig Bay on the east coast (map IX). In this particular area the relationships of a number of Lewisian dykes and pegmatites are moderately well displayed and it was hoped that it would be possible to determine the structural relationships and chronology of the intrusions and then extrapolate from these to other less well-exposed parts of the island.

Material was collected for thin section petrofabric study at only a few localities, including Halaman Bay where a strong lineation is imprinted on the gneiss oblique to the foliation (fig. XIII-2). From consideration of the extreme complexity of the structure of the Lewisian Gneiss it seemed unlikely that any clear picture would emerge from the study of preferred orientation of mineral grains, and support for this view is seen in the plot of quartz c-axes from the oriented specimen B7 collected at Castlebay (fig. XIII-8). If any strong pattern does exist it seems most likely that it would be displayed in a rock with a marked penetrative feature such as the lineation revealed on the sand blasted quartzo-feldspathic gneiss on the shore near Tangusdale at Halaman Bay. Orientated specimens were collected from this locality and three mutually perpendicular thin sections cut for microscopic examination. Specimens from two other localities apart from B7, were collected also, making three samples in all;

a) The Halaman Bay specimen (B47) of lineation parallel to 150°;

b) The Bruernish Point specimen (B633) of strong lineation parallel to 100° (fig. XIX-13);

c) The Bagh nan Clach specimen (B459) of ribbing parallel to 100°-120°.

The lineated gneiss from Halaman was considered to be particularly well suited to microscopic petrofabric investigation in that the lineation did not appear to be the consequence of dimensional parallelism of minerals of elongate (or columnar) habit but the effect of anisotropism of minute aggregates of quartz and feldspar presumably due to syntectonic lattice re-orientation. As such, it is more likely to be a feature of a late metamorphic phase rather than one inherited from an earlier deformation. This is on the assumption that for a given degree and style of deformation, optical reorientation is more likely to proceed to completion than is mechanical dimensional reorientation and by the same token likely to be more sensitive to the effects of succeeding deformations. Hence it was felt that the lineation displayed in the hand specimen should reflect one of the latest phases (if not the latest phase) of deformation in the Lewisian Gneiss of this part of Barra. For this reason thin section petrofabric examination was carried out in spite of the marked triclinicity of the symmetry of the overall structure, and in spite of the results obtained from the Castlebay specimen (fig. XIII-8).

A detailed study of non-penetrative structures like joints has not been made but plots have been made of the larger steep and vertical joints whose trends were determinable from aerial photographs (see section XVIII, p. 198).

2. Structural Features Considered

In the present investigation the following kinds of structures have been considered.

a. Planar structures

(i) Foliation. The attitude of the foliation was measured where-ever possible and recorded for all exposures examined. In many cases this varied so much over a single small outcrop that an estimated average attitude for the exposure was noted. In some cases too it was possible only to measure and record the trend of the trace of the foliation on the ground surface. The limiting factor in mapping most well-exposed areas was that which was imposed by the size of the notation on the field map. In areas where the attitude varied little, as in the south-east of Barra (map I), the number of attitudes recorded was fewer but sufficient to show that there is little significant change from one exposure to the next on the scale of the map. The trend of foliation is marked by solid lines on the finished map and where exposure is poor or absent the inferred trend is denoted by dashed lines (map X).

(ii) Septa. In a few restricted areas vertical septa form a prominent structural feature. These result from the development of mineral assemblages characteristic of lower metamorphic grade than the surrounding gneiss and are expressed in the form of ribs an inch or two high on the outcrop.

(iii) Cleavage. Cleavage fractures in the strict sense have not been recognized in the field. The trends of approximately vertical ribs of resistant gneiss of varying width up to approximately 2 inches representing the trace of the septa noted in (ii) above are believed in some cases to be related to fold axial cleavage. Smaller examples of a similar type of structure aligned parallel to fold axial planes have been encountered in various parts of the field (fig. XV-4).

(iv) Joints. The trends of the major steep to vertical joints have been measured from aerial photographs but have been recorded in only a few cases in the field. Measurement of the attitudes of joints in the field has not been included within the scope of the present investigation in view of the complexity of the structure.

b) Linear Structures

(i) Fold Axes. The attitudes of fold axes have been recorded wherever possible as the angle of plunge and bearing of plunge direction and are marked on the map with an arrow. As in the case with measurement of foliation the attitudes of the fold axes have not always been determinable and in many cases only the trend of the fold axial surface outcrop has been measurable. In these instances it has generally been possible to correlate fold axial trends and axial plunges as a result of examination of folds in better exposed coastal stretches and particularly also on the basis of the style of the folding in relation to foliation attitude.

(ii) Axial Surface traces. The trends of fold axial surface outcrops have been recorded for minor folds and these in most cases, with the notable exception of folds related to north plunging F_2 structures, are closely parallel to the trend of the fold axes.

(iii) Lineations. True lineation is of restricted occurrence in this field and has been measured and recorded in a manner similar to that used for fold axes.

The results of the statistical structural analysis, and the discussion of these, are given in section XVIII on page 175 after the sections dealing with the tectonic sequence.

Extensive use has been made of figures throughout, in order to reduce the bulk of the descriptive part of this work. The figures have been bound in a separate volume to facilitate reference while avoiding duplication, since many of them are referred to several times in the text.

III. TECTONIC HISTORY

A. Discussion

It is improbable that reliable evidence for more than about four superimposed periods of folding in the gneiss could have survived the effects of subsequent orogenies, especially as anatexis associated with deformation appears to have been both intense and ubiquitous. (At the start of the investigation two possible relationships between the migmatisation and the recognisable periods of folding suggested themselves. The first was that folding began following a phase of intense and widespread migmatisation which was responsible for the breakdown of continuous sheets of basic rock into the lenses of green hornblende and biotite rich rocks which occur throughout the gneiss. The second alternative was that evidence would be found for several migmatising phases, each associated with folds of a different period of deformation. Field evidence has shown the second of the two alternatives to be more nearly correct. The effects of anatexis and the origin of the migmatites are discussed in detail in section XIX).

Field evidence clearly indicates that the structural history of the gneisses is one of great complexity. Therefore it is unlikely that tectonic events other than those which produced a very strong imprint on the rocks will have left recognisable traces. The very latest deformational phases may be exceptions to this general rule. Bearing this in mind the following, albeit greatly simplified, sequence of events is pieced together from the accumulated field evidence and statistical structural analysis. There is much which does not appear to fit into the postulated pattern, and this is almost certainly due in part to the fact that isolated areas less strongly affected by later tectonic events will preserve records of earlier phases which have been obliterated elsewhere. In other cases structures which at first appeared anomalous have been found to dovetail neatly into the structural chronology as more and more data became available. For example, it was not until after several weeks in the field that conclusive evidence was found for the cross-cutting nature (and therefore igneous origin) of the Lewisian dykes and this fact then enabled further chronological ordering of the events recorded. In particular, remapping of the end of Leenish peninsula on a larger scale resulted in considerable subdivision of the Lewisian dyke series.

B. Summary of the Tectonic History

The following is a summary in chronological order of the events distinguished in the history of the gneisses.

The earliest recognisable evidence of deformation following the formation of the banding lies in the presence of hinges (frequently rootless) of isoclinal folds parallel to the regional banding in the gneisses. The overall trend of the regional foliation is approximately south-south-east (fig. XVIII-1), oblique to the line of the Hebridean chain. The attitudes of the hinges are in most cases extremely difficult to determine because of the infrequence of differential weathering and the hinges probably result from more than one very early episode of deformation whose folds were later overturned, compressed and sheared until ultimately their axial planes became more or less parallel. Associated with, or immediately after the isoclinal folding the area was subjected to regional metamorphism up to a grade at least as high as the amphibolite facies.

At some time after the latest of these phases of isoclinal folding, but prior to the shearing, basic to ultrabasic intrusions were emplaced within the gneisses. These were probably comparatively narrow (in most cases probably not more than five feet in width and generally much less) and have survived only as isolated strings of dark green lenses of almost pure hornblende. Possibly later still, and perhaps separated by other phases of deformation not recognized in the field, are several much larger intrusive bodies now recognizable as masses of grey, epidiorite gneiss mottled with small patches of green hornblende. These are usually subparallel to the foliation, and at one locality grade into a large mass of extremely coarse hornblende-bearing gneiss containing in the central coarse phase, individual, stubby hornblendes up to an inch and a half long. Other narrow amphibolitic bands, parallel to the foliation may have originated about the same time as sills. At about this time also there were emplaced ultrabasic masses now represented by almost pure pyroxene and hornblende gneiss like that at Balnabodach. The relationship between these rocks and the epidiorites is not exposed. Large basic and ultrabasic masses occurring at the east end on the north and north-east coast of Leenish are considered, purely on petrographic grounds, to be of the same age as the Balnabodach intrusives. Boudinage affecting the basic amphibolitic bands took place at some time before the next igneous intrusives were emplaced. Elsewhere on Leenish cross-cutting relationships of several basic to intermediate dykes suggest at least six phases of intrusion. Following the emplacement of the first series of igneous rocks of the Leenish Complex it seems likely that there was a further episode of deformation (F_1) represented now in some areas by folds plunging to the north-east and by the presence of quartzo-feldspathic pegmatite veins striking at 35°–50°. These are considered to have been emplaced along tension fractures believed to have opened up perpendicular to Pmax with the release of the stress responsible for folding and, like the pegmatite vein at Leenish (figs. XIX-1, 3), are sometimes of considerable size. The north-easterly striking pegmatite veins are cut by hornblende granulite and pyroxene granulite dykes of a type common on Leenish, at Ersary and near Balnabodach. Dykes of this type which can be seen to cut earlier dykes of epidiorite type in the vicinity of Loch Scotageary on the east coast are probably the most common and show the clearest cross-cutting relationships and indeed, their dykelike nature is so marked, on the east end of Leenish, that they cannot at a distance of a few yards be readily distinguished from dykes of post-Lewisian Permian or Tertiary age. In spite of the obvious variation from margin to centre to be seen in the field, the rock of these bodies is texturally clearly metamorphic when seen in thin section. In no instance has recognizable ophitic texture been seen under the microscope as is the case in dykes described by Teall (1885) and Sutton and Watson (1951). It is suggested, nevertheless, that those intrusives, which are the latest of all Lewisian intrusives recognized on Barra, might be equivalent to the dykes described as "pre Laxfordian" non-orogenic dykes by Sutton and Watson (1951). This of course implies that the earlier intrusives are representatives of igneous activity separating previous orogenies equivalent to the "Laxfordian". No case of Lewisian dykes cutting fold structures has been seen in the field, although dykes on the shore south of Brevig can be seen to have been emplaced later than detached fold hinges (fig. VII-14).

Throughout the field there are exposures of agmatite similar to that outcropping south of Bruernish Point (fig. XIX-13), which appear to be later than the latest phase of dyke intrusion because they contain fragments of hornblende granulite. Some at least of these are considered to have formed prior to the later phases of deformation already noted (F_4 and F_5) because they are affected by lineation due to the intersection of the outcrop surface with a planar structure striking 100°, parallel to the axial surface of late folds (F_4). They are also cut by pegmatite veins considered to be related to folds of later age.

On the shore west of Halaman Bay there are folds of pseudo-tachylite and flinty crush (parallel to the folded foliation) whose apices lie on a line trending 120°. This suggests folding of very early-formed pseudotachylite, since although the possibility of emplacement of pseudotachylite parallel to the already folded foliation must be admitted, invariably pseudotachylite veins at this locality display sharply cross-cutting relationships to the host rocks (fig. III-1). The present example thus suggests that the earliest recognised pseudotachylite and flinty crush was formed prior to folding across axial planes striking 120°. (See footnote 8, p. 150).

Following regional metamorphism up to pyroxene granulite grade and the very early period of thrusting responsible for pseudotachylite formation, and possibly after the anatexis and the development of agmatites of the type just mentioned, the first widely recognized phase of folding (F_2) took place. Structures of this style control the large scale variation of the regional strike from the general north-north-east trend. The largest macroscopic structure discovered is of this age and forms the peninsula at the north end of Barra at Scurrival (maps I, II). Smaller scale mesoscopic structures of the same geometric form can be seen throughout most of the field. The fold axial plane strikes approximately 120° and dips towards 30°; the north-eastern limb dips 25° towards 330° and the south-western (overturned) limb dips 65° towards 50°. The fold axis usually plunges at 25° towards 345°. Because of the geometry of the folds of this generation the 120° trending axial planar direction is the dominant macroscopically visible expression of the structure throughout the field. Quartzo-feldspathic pegmatite veins parallel to 120° which are therefore presumably of late F_2 age can be seen to cut the latest Lewisian dykes at Leenish.

A later phase of folding (F_3) is represented by the survival of many small scale (mesoscopic) folds generally with a wavelength of only a foot or two at most. These typically are symmetrical (or almost so) and open or moderately tight in style, trending at about 145°. Pegmatite veins striking at approximately 150° are associated occasionally (notably at Bruernish), where they cut agmatite (fig. XIX-13), and on weathered and eroded exposures, particularly on the shore at Halaman Bay near Tangusdale (figs. XIII-1, 2, 3), there is a very marked lineation plunging at approximately 10° towards 145°. This is due to a slight preferred orientation of quartz grains in minute elongate lenses or rods, sheathed in biotite producing a penetrative structure in the quartzo-feldspathic gneiss.

Later 100° trending folds (F_4) due to flexure followed by drag and incipient shear on planes dipping at approximately 80° to the south, form the most consistent fold direction seen in the field. Corrugations parallel to 100° affect 160° trending pegmatite veins on Bruernish (fig. XIX-13). The folds are characteristically, but not invariably, symmetrical open structures often only 6 inches to a foot across but sometimes reaching a wavelength of 10 or 15 feet and trending at 100°. In places in the field, especially on the east coast on Leenish and thereabouts, east-south-east trending pegmatite veins cutting south trending pegmatite veins and Lewisian dykes are interpreted as later injections into tension fractures parallel to the fold axial planes. A very prominent feature of exposures in the Scurrival-Eoligarry district is a marked ribbing approximately half an inch wide which stands in places as much as an inch and more above the surface of the exposure (figs. XIV-23, 24, 25, 26). This strikes in general at approximately 100° (although some strike at 120°) and is considered to be due to increased resistance of the gneiss following low grade metamorphism along preferred planes parallel to the axial plane of 100° folds. Similarly, a finer lineation at Bruernish Point (fig. XIX-13) is the result of analogous later stage retrogressive metamorphism. These features may be the result of very late phase metamorphic processes but in view of the fact that the effect is limited to very narrow planes parallel to the 100° axial planar strike of the F_4 folds it is thought they are likely to have formed immediately after the folding.

Folds of a final phase of warping (F_5) take the form of broad, open north-east plunging structures. In some exposures, particularly those on the coast at Halaman Bay (map V), F_2 and F_4 type folds can be seen to swing across these later folds (fig. XII-4). Broad, gentle, dome structures have been formed in this area, as a consequence of this deformation and in the north of Barra the limbs of the Scurrival structure probably owe their curvature to the effects of this later orogeny. The plunge to 280° of folds of F_4 style apparent at Doirlinn, south-east Barra and the reversal of the direction of plunge of some F_2 folds is similarly considered to be due to this latest deformation. It is probable that anatexis accompanied all stages of folding, with the possible exception of the less intense final north-east F_5 folds.

The final deformational phase recorded in the gneiss is the comparatively shallow, brittle style of the latest Hebridean Thrusting which transects all structures in the Lewisian Gneiss and appears to have caused some rotation of F_4 folds (figs. XVIII-10, 11). This phase precedes the emplacement of Permian and later dykes, themselves affected by comparatively recent faulting.

C. Outline of the Sequence

Phase 1. Processes leading to formation of original banding.

Phase 2. Isoclinal folding and regional metamorphism.

Phase 3. Shear folding.

Phase 4. Various igneous phases of the Leenish Complex.

a. Large basic intrusives. The Early Phase.

b. Ultrabasic intrusives (Hornblende dykes and coarse hornblende pegmatites). The Middle Phase.

c. Basic sills (Biotite gneisses). The Late Phase.

Phase 5. First north-east fold period (F_1) plus migmatisation and pegmatite vein injection.

Phase 6. Agmatite and boudin formation. ? Folds associated with boudins.

Phase 7. Later dyke emplacement.

a. Acid and intermediate dykes (Biotite gneiss). The Early Phase.

b. Basic dykes (Biotite gneiss). The Middle Phase.

c. Basic dykes (Hornblende and pyroxene granulites). The Late Phase.

Phase 8. Pyroxene granulite regional metamorphism.

Phase 9. 345° folding and pegmatite vein injection (F_2); preceded by the first thrust period?

Phase 10. 145° folding and formation of lineation, plus pegmatite vein injection (F_3).

Phase 11. 100° folding and pegmatite vein injection. Development of 100° septa and lineation (F_4).

Phase 12. North-east warping (F_5).

Phase 13. Thrusting.

Phase 14. Later 70° joint development; faulting.

Phase 15. Post-Lewisian dyke intrusion; faulting.

IV. ORIGIN OF THE FOLIATED GNEISSES

Consideration of the aspects of the gneiss of all exposures and comparison with the Lewisian Gneiss in other areas, particularly those containing metasedimentary rocks such as South Harris and Tiree, creates the overall impression that the foliation in the gneiss is parallel to some original non-metamorphic banding. In the case of the probable paragneisses of Scurrival the foliation is considered to be parallel to original bedding and throughout the remainder of the field, gneisses of presumed igneous origin are regarded as foliated parallel to original igneous layering analogous to that exposed in Scandinavia. These may have been derived from lava flows, sills or larger bodies, or from pyroclastics. The texture and macroscopic appearance of the orthogneiss succession in general is such as to suggest that it comprises the metamorphosed derivatives of either acid intrusions or lava flows into which sills of basic magma (dolerite or gabbro) were injected. All processes relating to the formation of the foliation are grouped under the first phase of the tectonic history (p. 40).

Occasionally structures have been observed which suggest emplacement of much larger bodies of igneous rock (fig. IV-1). In the photograph (fig. IV-1) the apparently tectonic contact between the light coloured intermediate gneiss and the basic gneiss on the right is in fact demonstrably a primary angular unconformity. This can be seen from the presence of thin stringers of the basic gneiss separating slivers of intermediate gneiss in what would be the shear zone if the contact were tectonic. The succession here is considered to young to the right and is thought to represent magmatic current bedding of the kind described from Scandinavian gneisses (Berthelsen, 1900; Rankama et al., 1963; Harry and Pulvertaft, 1963). In the present instance emplacement of magma of intermediate composition has been followed by an influx of basic magma which has infiltrated in thin tongues into the underlying rock and prised off thin layers from the floor of the magma chamber. The full extent of the primary current bedding cannot be determined because the structure has been obliterated by subsequent anatexis and formation of agmatite. Similar structures elsewhere in basic and ultrabasic gneisses in the Lewisian have recently been figured and described from the North-West Highlands (Bowes, et. al., 1964).

Banding which is considered to represent a second type of primary igneous banding has been recognized in the gneisses also. In this case its appearance suggests that the structure may have originated as a lava flow. Two exposures of this type have been observed in which basic hornblendic gneiss interfoliated in quartzo-feldspathic gneisses shows a transverse textural variation of a distinctive kind. From one side of the band irregular, ellipsoidal pockets approximately one inch to six inches long have weathered out imparting a coarse vesicular texture. The pockets are elongated parallel to the foliation and occupy about half the width of the band. The remainder of the rock retains a normal, fine-grained amphibolitic texture. One of the exposures is at the summit of the road between Castlebay and Brevig in the bank on the north-west side of the road, and the other is in the cliff above the school at

Balnacraig on the west coast (fig. IV-2). Examination of thin sections and polished slabs shows that the vesicular rock contains patches which are richer in plagioclase and have pyroxene as the dominant ferromagnesian mineral instead of hornblende. The vesicularity appears to be due to the weathering out of the feldspar.

There seems to be little doubt that these vesicular structures were originally igneous in character (or perhaps, although less likely, the result of metamorphic segregation) rather than sedimentary. In the unweathered state the rock appears uniform in hand specimen and only by close inspection of polished slabs does the increase in feldspar marking the sites of potential pockets become apparent. The possibility of their having been derived from conglomerates, for example seems therefore to be remote, both because of the uniformity of composition and because of the absence of sharply defined margins. If igneous in origin the asymmetrical nature of the bands suggests that they were emplaced with a near horizontal attitude as sills or flows rather than as dykes. The lack of substantiating evidence favouring an igneous origin, such as the presence of xenoliths derived from the surrounding foliated gneiss, or of fine grained margins, is inconclusive since the absence of these features within the limits of the exposures could well be due to the fact that the contacts of the basic bands with the surrounding gneiss are very likely to be tectonic. In this case shearing would have destroyed any original marginal features. At the same time it must be admitted that without making a detailed petrological study of this gneiss, apart from accepting it as a derivative of a vesicular basic lava flow, it is difficult to propose a mechanism to account for this texture whether it be igneous in origin or due to processes of metamorphic differentiation.

The foliation of the probable paragneisses of Scurrival is considered to be the direct consequence of an original lithological sedimentary banding. Interfoliated basic hornblende-rich bands possibly represent interbedded flows and later sills, modified and accentuated by metamorphic diffusion and recrystallisation. Apart from their resemblance in the field to gneisses of known sedimentary origin, the banding in the quartzo-feldspathic gneisses is, like sedimentary bedding, often due simply to variation in grain size from band to band rather than to difference in composition.

V. ISOCLINAL FOLDING AND REGIONAL METAMORPHISM

Prior to the first period of folding (F_1) numbered in the sequence recognized in the present work, very early flexural folds became appressed to form isoclinal folds during the second phase of the tectonic history outlined on page40 (figs. XIV-9, 13). Probably immediately after the formation of the isoclinal folds the whole of the region exposed at present was subjected to strong regional metamorphism. The grade reached at this time was at least as high as the amphibolite facies. But in view of the fact that relict minerals of higher grade have not been seen to be inherited on a wide scale throughout the field there is no evidence to suggest that the rocks reached a higher grade, although it is quite probable that such a higher grade was attained. During this metamorphism the basis of the present mineralogy was formed and the larger dark green stubby hornblende crystals of the thin basic bands in the gneiss grew and aligned themselves within the banding to form the present foliation. Alignment parallel to the axis of isoclinal folds resulted in a coarse lineation occasionally to be seen in the field to have a generally northerly trend (fig. XIII-1). Shear parallel to the limbs, followed later by conditions of plasticity, caused accentuation of the foliation by increase of preferred orientation and segregation of minerals into bands parallel to the foliation.

The quartzo-feldspathic gneiss more than any other has undergone semi-plastic deformation and evidence for this can be seen almost anywhere in the field. In consequence, rootless intrafolial fold hinges derived from these early isoclinal folds are composed of basic gneisses, normally amphibolites, which because of their resistance to migmatisation, have retained their identity during subsequent anatexis and plastic deformation of the enclosing, more acid members of the series. Tight, isoclinal flexural folds within apparently massive amphibolites are recognizable also, especially where the hinges are outlined by alignment of amphibole crystals (fig. V-1). This particular structural feature has generally been modified by the effects of subsequent shear directed parallel to the foliation to produce a more or less planar feature. Normally isoclinal folding in amphibolites can be recognized only when the rock contains remnants of fine, sheared-out hinges in thin feldspathic layers (fig. V-2), or minute folds picked out by individual feldspars and hornblendes (fig. V-3). Intrafolial fold hinges preserved in quartzo-feldspathic, rather than basic ferromagnesian gneiss, probably represent folds in early pegmatite veins which have become detached from their limbs by later shearing (fig. V-4).

Several larger mesoscopic early isoclinal folds whose identity is still preserved have been seen also (figs. V-4, 5, 6, VII-24, XII-5, 39). The general form and style of these is exemplified by the large fold on the hillside to the east of Tangusdale (map IV).

It is probable that folds of this style belong to several, now indistinguishable, very early phases of deformation and some at least may be the products of folding in sedimentary and layered igneous rocks before they were metamorphosed.

VI. SHEAR FOLDING

Shear, an important mechanism in the development and modification of foliation to the stage when it was affected by the orogeny producing the first decipherable structures (F_1), has maintained an important influence on the tectonic style of the gneisses until the latest orogenic phases. Its more recent affect is shown well by instances of tectonic contacts between essentially planar foliation and surviving hinges of tightly folded alternating basic and quartzo-feldspathic layers (fig. VI-1).

Shear folding, although grouped under Phase 3, is probably not referrable to a single identifiable phase of deformation and many of the numerous attentuated isolated fold hinges to be found floating in the gneisses have undoubtedly been continually modified since their ultimate origin as isoclinal flexural folds. However, there is every reason to suppose that the present form of these structures was largely determined by shear prior to the first of the five separate periods of folding (F_1 to F_5) to be discussed later. The effects of this shear, whether due to one or several phases of deformation, are discussed briefly in the present section.

Folds which owe their present form to modification by shear are fairly common and are characterized by knife-edge hinges and limbs which are planar, parallel to the foliation or stepped due to shearing out of subsidiary hinges (fig. VI-2). They are generally associated with strong alignment of minerals with elongate habit and the folds of figures V-2 and V-3 show clear evidence of this effect. Shear has been responsible also for the detachment of these fold hinges from their limbs (fig. VI-3), and this separation obviously took place prior to the folding of the periods F_1 to F_5 otherwise these later folds would themselves have been sheared out by the same mechanism. There is no evidence for such intense shearing of late folds (figs. VI-4, XIV-13).

Another consequence of early shearing is the breakdown prior to migmatisation of basic to ultrabasic intrusives, the latest of which provided the material for the small knots of green hornblende and pyroxene aligned in stringers throughout the gneisses. Because they have clearly been subjected to intense and prolonged shearing before reaching their present scattered, lenticular form, these are obviously distinct from, and very much earlier than those narrow examples, like the dyke at Rudha Liath (fig. VII-20), which still preserve a sheet-like form. They were probably originally basic to ultrabasic dykes, and in most cases of not very great width. These survive now as strings of isolated, comparatively small (usually with a diameter of one foot at the most) masses of dark green hornblende associated with a little green pyroxene, and generally rimmed with biotite in which {001} cleavage is aligned parallel to the margins of the knots (fig. IX-12). In some cases the masses exhibit a concentric structure due to radial variation in mineralogy, being composed principally of hornblende at the margin and richer in pale green clinopyroxene at the centre. In view of the complex history of the Lewisian Gneiss this distribution of ferromagnesians is probably a reflection of changes brought about during metamorphism subsequent to the emplacement of the intrusions rather than an effect of their original composition, particularly in view of their lensoid shape. Remnants of this nature are to be found scattered throughout the field.

These bodies are considered to be remnants of the only recognizable intrusives emplaced prior to the shearing which continually deformed the earlier isoclinal flexural folds aligned parallel to the present foliation. This intense shearing is considered to be the cause of the break-up leading to the partial assimilation of the material of the intrusions by later anatexis.

The hornblende knots in more or less massive feldspathic pegmatitic gneiss at Leenish may represent amphibolite fold hinges rolled up and sheared in this way. They have biotite margins probably as a result of breakdown of hornblende at the edges during shearing and introduction of potash. Some nodules about four inches across comprise almost pure biotite but, on the other hand, very small clumps one inch across are sometimes made up entirely of hornblende. This difference in mineralogy may be due to the fact that the smaller lumps could reorientate themselves more easily in response to deforming forces and thus would not have been subjected to such high shearing stresses as the larger nodules (fig. IX-12). If this is so then it seems likely that the potash metasomatism must to some extent have been related to, or controlled by shear stress.

It is believed that with the onset of the first of the following series of tectonic events, the basement consisted of a series of layered rocks which had been isoclinally folded and regionally metamorphosed and then subjected to shearing. Into this series basic igneous intrusives had already been emplaced on a number of occasions. From this time onwards the effects of different periods of deformation and intrusion have retained sufficient distinctive features to enable them to be differentiated and in some cases placed in chronological order. These phases, the effects of which have escaped later drastic modification, together constitute the tectonic history of the Lewisian which has been determined in the present work and each of them will be discussed in turn in the succeeding sections.

VII. EARLIER INTRUSIVES OF THE LEENISH COMPLEX

A. Relationship between Lewisian Dykes and Foliation

With the exception of dykes of basic and ultrabasic composition and those displaying very marked obliquity to the foliation, igneous bodies intruded very early in the history of the Lewisian complex are difficult to distinguish and indeed, in many cases unlikely to be recognised at all. This is because the criteria normally employed in the identification of intrusives, chilled contacts, contact metamorphic effects and even moderate angular differences between attitude of dyke and foliation, have frequently been destroyed long since by shearing, anatexis and regional metamorphic effects. This is shown for example, by the presence in the gneisses of stringers of green basic knots of the kind described in the previous section, which on rare occasions are recognizably arranged in linear fashion but which are individually of quite random orientation.

Hence the first clearly recognizable igneous event potentially capable of correlation in different parts of the field took place at some indeterminate time after the intense folding and shearing discussed in sections V and VI. It is suggested that this event involved intrusion of large basic masses of the type recognized particularly at Leenish but also in other places in Barra, especially on and near the east coast north of Leenish.

The southern end of Leenish comprises a complex of massive nebulitic and regularly banded pink and grey orthogneisses into which igneous rocks of acid to ultrabasic composition have been intruded at various periods in the history of the Lewisian Gneisses. The exposure is moderately good along the shore at the south eastern extremity where the cross cutting relationships of a variety of dykes are clearly displayed (map IX). The earlier igneous intrusives of this and related areas are collectively grouped under the heading of the Leenish Complex and the two groups of successive intrusions responsible for their emplacement comprise the events of Phases 4 and 7.

In only a few places were Lewisian dykes seen to have a strong angular discordance with the foliation. It might be argued that this tendency towards parallelism between dykes and foliation could be explained by later tectonic events. For unless one assumes that the fractures along which they were emplaced were fortuitously always subparallel to the foliation, or that the foliation exerted a strong control on their emplacement, it would seem reasonable to conclude that a mechanism such as foliation shear has subsequently brought the dykes closely parallel to the foliation regardless of any original angular discordance. Proposals of this nature have already been suggested and movement similar to that proposed by Sutton and Watson (1951) or the "garden trellis" mechanism of Sutton and Watson (1962) have been advanced to account for this effect. However, in this respect it is interesting to note the angular relationships between the foliation and successive dykes with visible cross cutting relationships in the Leenish area. These are shown diagrammatically in figure VII-1 which suggests that there is a regular increase in the angle between dyke and foliation with age. The accompanying table shows that the angular relationship between dykes and the foliation is variable (Table 3) and it is noteworthy that the sense and degree of angular relationship is not consistent throughout the field. Consideration of the angular relationships between quartzo-feldspathic pegmatite veins and foliation reveals a situation which is even more striking. For example, unsheared north-east trending rectilinear pegmatite veins varying in width from less than an inch to ten feet lie almost at right angles to the foliation but are transected by younger metabasic dykes which are subparallel to the foliation. Apparently reorienting mechanisms of the kind proposed by Sutton and Watson (1951, 1962) have not affected the quartzo-feldspathic veins in the same way as the dykes. Other early veins and dykes in the same area inclined at small clockwise angles to the foliation, if realigned by a (dextral) reorienting mechanism of this kind, must have been emplaced almost parallel to the foliation (fig. VII-2a). If this is not so, then the shear must have been sinistral in which case, later dykes now inclined <u>anticlockwise</u> at small angles to the foliation must have been intruded parallel to the foliation (fig. VI-1-3b) because dextral rotation would have brought the early clockwise dykes farther from the parallel position (fig. VII-2a) whilst shearing the later dykes into an orientation closer to that of the foliation (fig. VII-2b). Such evidence of foliation plane shear as has been seen in the field suggests that this has been dextral (figs. XIX, 5, 6). In any case shear reorientation cannot have accounted for the near parallelism of both sets of dykes (inclined clockwise and anticlockwise) and the foliation.

Table 3. Relationships of Lewisian dykes to foliation

6" Aerial Photo No.	Locality	Average dyke trend	Inclination to foliation a	b	c	Average strike of foliation.
1165	Fiary	10°		b		50°
3459 (25")	Orosay	165° & 90°	a	b	c	150°
3467	North of Cora Beinn	170°	a		c	0°
3484	Ruleos	170°–120°		b	c	120°
3484	Loch Obe	160°		–		40°
3487	Bruernish village	170°–160°	a	b	c	150°
4476	Rudha Mor	170°			c	170°
4479	Leenish	170°			c	170°
4484	Rudha Liath	150°	a	b	c	50°–0°
4484	Loch Obe entrance	30°	a			170°
4486	Bruernish	40°–0°–170°	a	b	c	50°–0°–150

a. Dyke inclined clockwise to foliation
b. Dyke inclined anticlockwise to foliation
c. Dyke parallel to foliation.

Yet another possibility which might be considered is that the direction of shear has changed between successive dyke intrusions; or again, that significant shearing has taken place at only one period, namely after the emplacement of the latest dykes. Both of these appear to require circumstances of timing and direction of shearing beyond those to be reasonably expected in nature.

The effects of an equal amount of two dimensional shear on lines inclined at different angles to the shear direction is shown in figure (VII-4). From the diagram (fig. VII-4) it can be seen that before shear can materially affect the original orientation of a dyke its direction must be inclined to the plane of the dyke at an angle of about 20^{o} or more. That is, the shear direction must lie within a cone of semi-vertical angle of 70^{o} whose axis stands normal to the dyke (fig. VII-5). Although this suggests at first sight that the number of possible effective shear directions is very great, on consideration it can be seen that this is not the case because the shear is parallel to the foliation (confined to a plane) thus a limiting factor is immediately introduced. The inclination of the foliation (shear) surface to the dyke determines the range of possible shear directions within the plane. If the foliation is perpendicular to the dyke then the possible shear directions lie in an arc of about 140^{o}, 70^{o} either side of the normal to the dyke (fig. VII-5). For all other angles of inclination of the shear surface less than 90^{o}, to a limit of 20^{o}, the number of possible effective shear directions becomes reduced until at

20^{o} there is theoretically only one direction (fig. VII-5). This limitation further reduces the possibility of conditions arising which are likely to favour effective dyke reorientation by foliation shear.

On the other hand, if it was possible for shear to act as an effective means of reorientation, it becomes necessary to consider whether or not this mechanism is likely to result in ultimate parallelism between dykes and foliation, and if so, under what circumstances this can take place.

Examination of the mechanism of shear perpendicular to the line of intersection of dyke and foliation (fig. VII-6) shows that rotation of the dyke effectively takes place about an axis which is the intersection of dyke and foliation, and continued shearing will ultimately bring the two planes close to parallel. Furthermore, in exposures parallel to the axis of rotation both dyke and foliation, from the time of intrusion, will always be apparently parallel, whereas exposures normal to this direction will indicate at the outset the true angular discordance which will diminish with continued shear. Exposures with attitudes intermediate between these two extremes will show corresponding variation in angular discordance.

Consideration of the general case where shear is oblique (not perpendicular) to the line of intersection of dyke and foliation reveals an interesting set of conditions. Here the situation is one in which rotation takes place about an axis normal to a plane containing the shear direction and the normal to the shear (foliation) surface (fig.

VII-6). Provided the direction of shear remains unchanged the axis of rotation remains constant in attitude (considering only simple shear) as does the attitude of the line of intersection of the two surfaces. This line of intersection is an axis of apparent rotation and is oblique to the plane in which rotation takes place. The constancy of attitude of the line of intersection between dyke and foliation can be envisaged readily if one considers a single foliation or shear slice. This, even when infinitely thin, moves bodily parallel to the direction of shear (fig. VII-7), so that the line of intersection moves parallel to itself in space. Thus for affine shear the dyke remains statistically planar in character whilst changing its attitude in space.

If the dyke is considered to be of considerable extent, isotropic and sufficiently rigid to be able to move relative to the foliation in a direction parallel to the contact (rather than by movement in segments in slices of gneiss parallel to the foliation), then rotation in space abouts its inter-section with the foliation would effectively produce the same reorientation, but by a different mechanism. Under these circumstances there would be synchronous relative movement between the dyke and the foliation at the junction with each shear surface along a line parallel to the axis of rotation and oblique to the direction of shear. At the same time the shear planes would have to move closer together, therefore with consequent thinning of the foliation.

A simple model of this mechanism can be constructed from two vertical rectangular sheets of wood or cardboard standing parallel to one another and normal to a plane (horixontal) surface. To the side of one, a narrow rectangular third sheet of wood is hinged at any angle other than 90° to the horizontal and this fits into an oblique slot of the correct width grooving the other sheet from top to bottom parallel to the hinge line (fig. VII-8). The vertical sheet bearing the hinge then represents the neutral shear slice, the smaller, inclined hinged sheet the dyke, and the other vertical sheet an active shear slice. The hinge represents the intersection of dyke and shear surface (foliation) and the axis of rotation of the dyke.

As the "dyke" rotates towards an attitude parallel to the "foliation" it moves along the groove relative to the moving shear slice in a direction <u>parallel</u> to the axis of rotation. In deformation of this "oblique" type where the intersection of dyke and foliation is the axis of rotation it is seen that the direction of shear in the dyke relative to the foliation is parallel to the shear surface and to the axis of dyke rotation but inclined to the direction of shear between the shear slices (foliation surfaces).

If this type of deformation has in fact taken place then shear between adjacent foliation surfaces and between foliation and dykes has not been parallel, so that inhomogeneous shear has been produced in a single deformational phase. This mechanism in part might be the true cause of shear effects seen in sheared and metamorphosed dykes rather than shear parallel to the direction of movement of the shear slices. In this case shear directions determined in deformed dykes would not be simply related to foliation shear directions.

To obtain such a mechanical arrangement the following conditions must obtain. In order to maintain its identity the dyke as a whole must act in a coherent manner and would therefore have to be fairly thick and not subjected to extreme anatectic conditions. If during shear of this nature there was no significant thinning of the foliation, the dyke would have had to possess high tensile strength because it would have been subjected to extreme tension while moving through the foliation parallel to itself but oblique to the direction of foliation shear. In such a case the resultant shear in the dyke would not lie parallel to the intersection of dyke and foliation but would be in a direction deflected by a small angle towards the perpendicular to this direction in the plane of the dyke. The angular direction would depend on the lack of thinning of the foliation (fig. VII-9).

Extreme tensile stress under these conditions of shear would probably result in mechanical failure of the dyke and breakdown into lenses, particularly as the dyke would be corrugated by each shear lamina (fig. VII-9c) thus resulting in restriction of movement through the foliation. It is thought that deformation of this type of shear of rigid slices not necessarily parallel to the foliation, is responsible for the lenticular nature of the dyke below the Thrust at Bruernish and on Orosay, Traigh Mhor (map I) and deformation of a similar nature probably produced the very early, irregular green hornblende lenses mentioned earlier (p. 50). Lenses formed in this way would show rotation due to greater (relative) translation across the lenses in a direction perpendicular to the line of dyke and foliation intersection (fig. VII-9).

In the first, or parallel case cited (shear between adjacent foliation segments), the direction of shearing within the dyke would lie in the plane of rotation containing the direction of foliation shear and the normal to the shear surface (foliation) and in this case would be in the same direction as the shear between the foliation surfaces (fig. VII-6).

Shear reorientation in actuality is probably a combination of both mechanisms and as such the effects seen in the field would probably prove to be difficult to analyse.

Shear sufficient to effectively reorientate dykes relative to foliation from perpendicularity to parallelism is most likely to take place by the second, or "oblique" mechanism which requires a shear slip to shear plane separation ratio of the order of 3:2 assuming infinite thinning of the foliation. At the same time the amount of shear across the foliation parallel to the dyke or thinning of the foliation, would be unreasonably large. Measurable examples of rotated boudins and other structures in the field indicate that this ratio, assuming free rotation of the boudins is something like 1:8, a much lower order than that required to bring perpendicular dykes parallel to the foliation by this method of shear. By the parallel shear slice mechanism the ratio of shear to shear plane separation necessary to produce the same effects exceeds 10:1 (fig. VII-4) and is therefore even more unlikely to be achieved.

For either mechanism or combination of the two, on an exposure parallel to the direction of foliation shear and perpendicular to the shear planes (foliation) the apparent attitude of the dyke in relation to the foliation changes constantly during shear, the angular difference becoming steadily reduced. Consideration of an exposure perpendicular to both the foliation and the direction of shear indicates that the rate of change in angular relationships between the trace of the dyke and that of the foliation will depend on the angle of inclination of the dyke to the outcrop surface (fig. VII-10). The orientation of a dyke steeply inclined to this surface and thus only gently inclined to the direction of shear which then lies outside the 140° cone discussed earlier (fig. VII-5), will be affected only slightly by shear. Hence under these conditions, if the dyke is markedly discordant to the foliation this discordance will change little and if it is parallel it will remain parallel. If on the other hand, the dyke is only gently inclined to the outcrop surface and thus steeply inclined to the direction of shear, slight displacement will cause marked reorientation. This reaches a maximum when the dyke is parallel to the surface of the exposure and therefore perpendicular to the shear direction whereupon its intersection with the foliation is perpendicular to the direction of shear.

For exposures perpendicular to the foliation and parallel to the shear the effects will depend on the original angular difference between the trace of the dyke and the foliation and for exposures perpendicular to both the foliation and the direction of shear the effect will be inversely proportional to the steepness of inclination of the dyke to the exposure and independent of the angular difference between the trace of the dyke and the trace of the foliation. The change in angular relationship between dyke and foliation for a given amount of shear oblique to the dyke, in exposures nearly parallel to the foliation (and therefore shear) is negligible. On exposures with attitudes lying between the three examples described the effects will be correspondingly modified.

Before apparent parallelism between dyke and foliation would be observed as a result of moderate "parallel" type shear, it will be seen from the cases just outlined that the dykes must always be viewed on a surface oriented normal to the axis of rotation and parallel to the shear direction. Therefore to observe this effect on a horizontal exposure, shear must have been more or less horizontal, and in fact, fulfillment of this condition seems not unreasonable. If the foliation is steep to vertical then dyke emplacement must itself be along fissures inclined close to the vertical. This condition also appears to have been fairly consistently fulfilled in the present field and suggests, incidentally, that where dykes have been mapped there has been little major change in the attitude of the Barra gneisses since dyke intrusion. This of course agrees with the premise which forms the basis of much of the structural interpretation; namely that there has been little major tectonic reorientation since F_2 folding.

For the reasons outlined on the preceding pages, however, it has been concluded that shear reorientation has not been a major contributory factor in the establishment of the present attitude of the Lewisian dykes in this field.

What is regarded as fairly conclusive field evidence against shear reorientation lies in the existence of two branching, garnet-pyroxene-hornblende granulite dykes each 100 yards wide, which outcrop three quarters of a mile apart near Balnabodach. These both belong to the latest, 7c phase of intrusives but the eastern dyke near the coast trends north-westward and cuts the foliation at 90° while that to the west of the three small lochs near the settlement begins with a north-east trend cutting the foliation at 40° and then swings north to north-east, parallel to the foliation (map I) which itself changes strike from 170° through north, to 60° near the edge of the overthrust sheet. Earlier consideration of possible folding or thrust drag having affected the strike of the foliation subsequent to dyke emplacement was abandoned after discovery of the eastern north-west trending dyke. Stereographic plotting of the attitude of the foliation in this locality does not produce a pattern in agreement with any of those recognized for the late fold periods but the plan of the trace of the foliation very strongly suggests the form of a large F_2 fold. The steepness of the attitudes recorded on the north limb near the thrust is probably due to later folding on axes trending 100°. It is concluded therefore that the strike has maintained this attitude with little modification at least since immediately prior to the intrusion of the two dykes considered. Further evidence lies in the fact that from the eastern of these two dykes thin tongues have been seen to branch off into the country rock. It is not thought that these would have survived extensive shear between the main body of the dyke and adjacent gneiss.

Next to the case just considered the strongest evidence for the relative unimportance of foliation plane shear as a orienting mechanism lies in the rectilinearity of large quartzo-feldspathic veins like that shown in figure XIX-1, and also in other even narrower veins. This vein trends at 50°, crossing foliation which strikes at about 160° to which it thus lies almost at right angles. But, as can be seen from the figure, it is nevertheless remarkably straight, whereas had it owed its present orientation to the action of shear, it is unlikely that this would have been so regular (that is affine) as to preserve such rectilinearity (figs. VII-11, XIV-23). Nor is there evidence of abrupt changes in direction of pegmatite veins transecting foliation and dykes at high angles where the veins pass from dykes to quartzo-feldspathic gneiss, a rock type which is almost certain to respond differently to shearing than the pegmatites (figs. VII-12, XIX-1), particularly if conditions of incipient migmatisation obtained.

Other, but less decisive, evidence is to be seen in the relatively slight preferred orientation of minerals in the intrusives, particularly in the latest of the dykes which still preserve a granular texture.

But later regional metamorphism could be held responsible for obliteration or modification of this effect, although earlier dykes appear to show a progressive increase in mineral alignment with age. The fact that contacts between some dykes and adjacent gneiss or crosscut dykes often appear to be unsheared further suggests that, although shearing undeniably has been a slight contributary factor in the attainment of the present orientation of the dykes, whether they be near parallel or not to the foliation, it is by no means the principal cause. Field relationships show fairly conclusively that the orientation of dykes relative to the foliation is a primary one, due to their emplacement.

On the basis that shearing has not greatly affected their orientation, correlation of pegmatite veins trends with those of axial planes of earlier folds is used in the subdivision of the tectonic chronology. Certainly the age relation between the various pegmatite veins agrees closely with that determined independently elsewhere for folds considered to be genetically related. Therefore until such time as conclusive evidence to the contrary is available, or until absolute ages or other equally rigorous methods can be employed, pegmatite veins will be used as an aid to distinguishing between different phases of igneous activity.

It is hoped that the following succession which has been determined will serve in the future as a basis for the further investigation of the Lewisian intrusives into the gneisses of Barra and the adjacent small islands until such time as further information necessitates modification. From field evidence the following table has been compiled to show cross cutting relationships and petrographic similarities between the various intrusives (Table 4).

Table 4. Age relationships of the Leenish Complex

	Dyke specimen number	Transects	Description	Petrographic correlatives
LATE	728		Dark grey gneiss with relict igneous texture	607, 613, 614
	733	740		
	734	736	Grey hornblende-hypersthene granulite and amphibolite	
	735	745		
	739	737		
	740	?736 737	Grey brown biotite gneiss.	721-741
	747	736	Grey hornblende-hypersthene granulite with relict igneous texture	
	736	745	Red weathering brown biotite gneiss	X (not collected)
		737		
	747	X		727
EARLY	X	746	Do.	
LATE	745	?737	Faint grey biotite gneiss	726, 731, ?746
EARLY	737		Amphibolite	
		?All cut 750 Country epidiorite		
LATE	732	731	Grey brown biotite gneiss, (Basic).	730
EARLY	731	?750	Reddish brown biotite gneiss (Intermediate)	726, 745
LATE	742	741	Fine grained biotite gneiss	745, 746
EARLY	741		Coarse grained biotite gneiss	
LATE	726	724	Biotite Gneiss	753, 754, 746
EARLY	724		Coarse amphibolite	725
LATE	752	750	Biotite gneiss	736
EARLY	750		Hornblende quartzo-feldspathic gneiss	
	749	750	Biotite gneiss.	746, 748
	730		Brown biotite gneiss	732

The known relationship between dykes and cross cutting quartzo-feldspathic pegmatite veins is shown in Table 5.

Table 5. Age Relationships between Leenish dykes and pegmatite veins

		Transect
LATE	90°–100° veins	Dyke 734
	"	Dyke 720
	"	Dyke 722
	"	Dyke 730
EARLY	" and 120° quartzo-feldspathic-veins	Dyke 733 etc.
LATE	2 inch 110° quartzo-feldspathic veins	6'+, 50° quartzo-feldspathic
EARLY		
LATE	Dyke 733 etc.	6'+, 50° quartzo-feldspathic
	Dyke 729	
	Dyke 730	
	Dyke ? 732, 731	
EARLY		
	6'+, 50° quartzo-feldspathic vein	8' biotite dyke

The cross cutting relationships between the dykes and the quartzo-feldspathic veins are shown diagrammatically in figure VII-1.

From the above sequences the following series of events is derived, based partly on cross cutting relationships and in part on correlation on petrographic grounds. The numbering used in the sequence follows that in the Outline of Sequence on pages 40 and 41. The intrusives of Phase 4 are all distinctive in having moderate to strong preferred orientation of their minerals and this imparts to them a definite lepidoblastic texture (Harker, 1950, p.201).

Phase 4. First series of Leenish intrusives.

a. Early phase. Intrusion of basic bodies now represented by basic hornblende gneisses and epidiorites.

b. Middle phase. Intrusion of basic to ultrabasic dykes now represented by hornblendic and pyroxenic gneisses.

c. Late phase. Intrusion of basic to ultrabasic dykes now represented by biotite bearing gneisses.

Phase 5. First north-east fold period (F_1), anatexis and injection of north-east quartzo-feldspathic pegmatite veins.

Phase 6. Anatexis and agmatite formation.

Phase 7. Second series of Leenish intrusives.

a. Early phase. Intrusion of acid and intermediate dykes, now represented by biotite bearing gneisses.

b. Middle phase. Intrusion of basic dykes now represented by biotitic and hornblendic grey gneisses.

c. Late phase. Intrusion of basic hornblende and hypersthene dykes which cut north-east quartzo-feldspathic veins (fig. XIX-1) and are themselves cut by narrow east trending quartzo-feldspathic veins. These are represented now by hornblende granulites and pyroxene granulites.

B. First Series of Leenish Intrusives

1. Early Phase (4a).

The apparent similarity in the field and in hand specimen between some crosscutting dykes (fig. VII-13) tends to suggest that these might in fact be closely related, being early and late intrusions of approximately the same phase of igneous activity. Thin section examination of the two dykes in the figure shows that while one (specimen 732) possesses a distinct granoblastic (Harker, 1950, p. 202) texture the other earlier dyke (specimen 731) is distinctly lepidoblastic (Harker, 1950, p. 201) with strong alignment of mineral grains. Compositionally the two are quite distinct also. In this case then, there is clear evidence for at least one deformational phase of considerable intensity between the intrusion of the two dykes and this serves to support the conclusion that the sequence of events proposed on pages 40 and 41 is probably grossly simplified, particularly in view of the fact that several orogenic phases have been recognized since the latest of the igneous intrusions.

The distinction between dykes of different ages is not always as difficult as in the case just noted. This can be seen from photographs of unrelated dykes on the south shore of Brevig Bay (fig. VII-14) and on the shore at Leenish (fig. VII-15).

Intrusives of Phase 4a exemplified by specimens 535, 593, 594, 602, 636, 720, 724, 725 and 750 are characteristically porphyroblastic (Harker, 1950, p. 202) in texture and exhibit a coarsely mottled appearance in the field (figs. VII-16, 17). The porphyroblasts appear to be relict and comprise large grains and clumps of grains of pale green clinopyroxene (sometimes with a little dark green hornblende) or plagioclase nested in lepidoblastic aggregates, and stringers of brown biotite flakes and elongated hornblende crystals interspersed with equant plagioclase granules. Associated with the porphyroblasts are single grains and elongate patches of opaque minerals (fig. VII-18). The approximate mineralogical percentages are as follows:- porphyroblastic strained and bent oligoclase or green clinopyroxene 25-40 per cent, hornblende 10-25 per cent, biotite 10-25 per cent, opaque 10 per cent, apatite 2-3 per cent.

Texturally, gneisses of this type give the appearance of metamorphosed basic intrusives of deep seated origin or large size, which have cooled slowly and have undergone a considerable degree of deformation, including shear. The presence of brown biotite suggests difference in original composition rather than introduction of potash although it is noteworthy that nearly all the earliest intrusives contain biotite in appreciable amount. The possibility of potash introduction brought about by injection of quartzo-feldspathic pegmatites following migmatisation at depth has been considered, but the presence in the same area of basic dykes only 12 inches wide (specimen 737) which are notably biotite free suggests that mineralogy is controlled by original composition. Chemical analyses and accurate age determinations of dykes and enclosing gneisses would be necessary before this question can be settled finally. If potash has been introduced one could reasonably expect the narrowest of intrusive bodies of the same age in a particular locality to show the greatest effect.

Generally the margins of the intrusions of this group are ill-defined and frequently the contacts with the enclosing gneiss are tectonic. All those mapped occur in the area from Leenish, north to Bruernish in the overthrust gneisses, but in common with nearly all the Lewisian intrusives they appear to be confined to the eastern part of the overthrust sheet. Like igneous bodies of the earliest phases they are sinuous and lensoid in form.

2. Middle Phase (4b).

Intrusives of Phase 4b are basic to ultrabasic in composition and range from large irregular and ill-defined bodies, often lensoid in form, to narrow, parallel sided dykes. Examples of the large intrusives are afforded by specimens 123, 197, 474, 475, 548, 590, 637, 639, 640, 684, 727 and 747 while specimens 240, 609, and 737 are representative of the dykes whose thicknesses are measurable in inches and which rarely attain widths greater than a foot.

Two examples of dykes will be described. The first of these (specimen 609) is exposed as a thin sheet lying across banded basic gneisses on the shore immediately south of Rudha Liath north of Ersary (fig. VII-19). It is about 3 inches thick and is coarser in the centre where it comprises almost pure basic dark green hornblende with a little pale green clinopyroxene. The margins are finer grained and the rock at one margin contains up to 60 per cent of scapolite and the other about 20 per cent of small pale green clinopyroxene grains. The composition of this gneiss is very close to that of the green lenses mentioned on page 49 which are considered to be remnants of very early basic dykes.

The second example (specimen 737) has a nematoblastic texture and comprises about 80 per cent dark green hornblende, 15 per cent andesine and 5 per cent pale green clinopyroxene. Faint banding due to variation in grain size can be discerned in thin section (fig. VII-20).

The larger intrusives which presumably acted as reservoirs and feeders for some of the smaller dykes have scattered distribution along the east coast and inland and similar gneiss occurs in the cores of some folds (fig. XII-5) and as small isolated lenses in foliated basic gneisses at Bagh nan Clach (fig. VII-21).

In thin section the rock is seen to possess a very coarse granoblastic texture which appears to be at least in part an inherited igneous texture (fig. VII-22). It contains between 35 per cent and 55 per cent strongly pleochroic hypersthene, about 20-35 per cent pale green hornblende, 10 per cent biotite and sometimes up to 10 per cent olivine and up to 5 per cent scapolite. Opaque minerals comprise approximately 2 per cent of the whole. Poeciloblastic (Harker, 1950, p. 202) or relict poikilitic texture is common in the larger hypersthene grains.

Although these bodies contain large amounts of hypersthene almost completely unaffected by replacement due to retrogressive metamorphism they are considered to be very early intrusives because of their consistently irregular lensoid shape. The fact that they have preserved to some extent their original texture and do not, with the exception of specimen 475 from the core of a tight isoclinal fold, exhibit strong mineral grain alignment in spite of their long tectonic history, is put down to tectonic resistance due to their large size compared with other and later bodies which show more marked textural and mineralogical changes.

Also considered to belong to this group of intrusives are coarse hornblende pegmatites at the southern tip of Leenish and on the shore at Ersary (fig. XIX-21). As far as can be determined, those bodies that are moderately well exposed on the shore at Leenish and north to Ersary and Balnabodach appear to dip or plunge consistently to the south depending on whether they are sheetlike or lensoid in form.

3. Late Phase (4c).

Dykes of the next series of intrusives (Phase 4c) are narrow, 6 inches to 18 inches wide, and clearly defined. They are distinctly more leucocratic than any of the preceding types. Examples are specimens 544, 672, 726, 731, 741, 742, 745, 746 and two coarser specimens 748 and 749.

Texturally both types are strongly lepidoblastic, the dominant ferromagnesian mineral being biotite which makes up between 60 per cent and 75 per cent of the dark minerals present (fig. VII-23). Their composition is as follows; (quartz) and feldspar (andesine) 70 to 80 per cent, biotite 10 to 15 per cent, hornblende and hypersthene 5 to 10 per cent, opaque minerals about 3 per cent and apatite approximately 2 per cent.

Although they exhibit sharp boundaries and distinct crosscutting relationships with the foliation and other dykes, and weather to a reddish brown, their pale grey colour in the field tends to make them much more ghostlike in outline than most other Lewisian dykes.

Folded hornblende gneisses on the south-east coast of Ru fear Vatersay appear to plunge to the north east (fig. VII-24). They are similar in style to the folds in Bagh nan Clach and the Croig and smaller folds on their crests plunge to between 20° and 40°. These basic bands probably represent early intrusives emplaced parallel to the foliation, and the presence in the fold hinge nearest the camera of what appear to be relict xenoliths of grey gneiss similar to that enclosing them attests to their originally igneous nature. Unfortunately their relationship to other intrusives is not shown. Much smaller detached hinges with a north-east trend on the south shore of Brevig Bay (fig. VII-15) possibly represent the remnants of dykes of this age.

More sharply defined biotite gneiss dykes cutting dykes of Phase 4c and large north-east trending quartzo-feldspathic pegmatite veins which themselves cut biotite dykes similar in composition and texture to those just described are relegated to the later distinct phase of igneous activity, 7a.

VIII. FIRST NORTH-EAST FOLD PERIOD F_1

Following the intrusion of the igneous bodies of Phase 4c, emplaced presumably in comparatively rigid rocks under conditions of tension, there was a return to a deep seated environment. The rocks became more plastic and were subjected to deformation, probably involving compression, during which folds of the first generally distinguishable group were formed. Examples of structures developed during this period outcrop sporadically throughout the field and take the form of moderately tight more or less symmetrical (i.e. orthorhombic) folds formed during the fifth tectonic phase.

The axis of this folding now trends north-east in the overthrust block of gneiss along the east coast where the foliation strikes generally south-south-east (fig. XVIII-10). Some of the tighter of the open folds plunging to about 30° rather than north-east may belong to this episode of folding, although the majority of these belong to the final north-east fold phase, F_5. This orogeny (F_1), like most others, was associated with local migmatization at depth. At shallower levels it is probable that at least incipient axial plane cleavage developed and it is thought that with release of compression after folding, pegmatites originating locally and from deep seated anatexis were intruded into the higher country rocks parallel to axial planar directions. Certainly in the Leenish area which appears to have been little affected by later folding, pegmatite veins with a north-east trend are cut by the latest of the Lewisian dykes of Phase 7.

Early in the present investigation the presence of apparently anomolous north-east trending folds in isolated occurrences throughout the field and the discovery of a few very early north-east striking quartzo-feldspathic pegmatite veins suggested that traces of an early north-east fold direction have survived. It was hoped that firm evidence for (or against) the previous existence of approximately 30° trending folds would be found east of the Thrust.[2] Here there are areas where the strike of the foliation is so regular that it might be expected that the trend of early fold axes would still maintain the same or similar orientation in relation to the strike. Where foliation is less regular, as happens frequently west of the main Thrust and in the north of Barra, dispersion about later fold axes is likely to have obscured the simplicity of any early pattern. Fold axes from the east coast plotted in equal area projection do in fact show a distinct grouping of plunges to the north-east, but these are likely to be predominantly folds of F_5 generation (fig. XVIII-10).

The field evidence for this phase is discussed below. Use of structural analysis employing plots on equal area projection is necessarily limited by the triclinicity of the fabric symmetry.

At several localities on the east of the island such as Ru fear Vatersay (fig. VII-24), steep to vertical foliation associated with folds

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2. Above the beach at Mingulay there is a 30° trending mineral rodding in amphibolite similar to the elongate mineral aggregates in the hornblende and pyroxene granulite dykes north of Rudha Liath and this suggests that this phase of folding took place after the latest dyke intrusions possibly, in association with the pyroxene granulite metamorphism. Opposed to this is the field evidence at Rudha Liath of granulite dykes cutting across a structure apparently related to F_2 and this suggests that the pyroxene granulite metamorphism followed, rather than preceded F_2.

strikes approximately 30°. Because of subsequent folding, especially when this was on a large scale like that about 120° trending axial planes, the likelihood of finding regularly-striking 30° folds is slight except in areas which were not greatly affected by this later folding. Any attempt to check the angular relationships between north-east trending fold axes and attitudes of foliation at, say Leenish where related pegmatites strike 30° or at Halaman Bay where 30° plunging folds occur on the shore, is likely to be defeated by the complex tectonic history of the gneisses. The following possibilities can be considered, albeit with little likelihood of reaching any conclusive findings: If, in the localities being compared, the strike of all the fold axes was found to be the same (i.e. 30°) and the general strike of the foliation variable this would mean, a) the folds described belong to the early phase of deformation but the foliation has not been greatly reoriented in these areas since the 30° folding phase or, b) all 30° folding was much later in the overall sequence of events.

On the assumption that large scale changes in strikes of foliation are due to folding about north plunging axes of the Scurrival type (the largest folds determined are of this style - F_2, Phase 9), the direction of plunge in east-north-east striking foliation of axes which plunge steeply north-east in south-south-east striking foliation was determined for localities at Scurrival and Halaman Bay (fig. VIII-1). The plunge was found to be in the region of 20° to

30° towards the north-west and the few axes plunging at about 20° towards 320° in the area south of the beach at Halaman Bay where the foliation strikes approximately E.-W. possibly represent folds of this generation. However, the number of axes measured is quite insufficient to prove this point conclusively (fig. VIII-2). It is also possible that a few axes with similar plunge at Balnabodach where the strike swings to the east-north-east may belong to this group.

In view of the low order of symmetry of the overall fabric, it was not considered likely that any further attempts at proof or disproof of the existence of these structures would be rewarding. On the basis of their style and scattered distribution, moderately compressed north-east plunging folds are separated as the products of a distinct early period of deformation. A plot of all minor fold axes and their relation to foliation does show a scatter in the first quadrant 0°-90° which, although it probably includes several axes of the final north-east folding from areas where the foliation strikes south-south-east, is probably reinforced by small folds of the first north-east folding (fig. XVIII-8).

Folds whose axial planes trend approximately 120° exposed west of the road at Brevig appear to have crests plunging at about 30° but this may be an illusion due to the slope of the surface of the exposure (c.f. p. 119). Associated with these there are, however, thin and rather irregular quartzo-feldspathic pegmatite veins which trend at

30^{o} parallel to the axial crests of faint and somewhat disturbed asymmetrical folds whose west limbs, like those of 120^{o} type folds are much steeper (and even vertical) than the north-east limbs (fig. VIII-3). Although in most respects these look very similar in style to the Scurrival F_2 type folds the difference between the trends of their axial planes, 30^{o} rather than 120^{o}, is quite distinctive and they tend to be prone to brecciation and much less regular, a feature to be expected in the products of much earlier phase of folding. This suggests then, an early phase of folding (producing folds presently trending parallel to 30^{o}) resulting from movement of a type similar to that responsible for the F_2 folds with their associated 120^{o} axial planar trend, but with a different direction.

Near Ersary, where the strike is east-south-east a series of small asymmetrical folds whose axes plunge to about 30^{o} have curved axial planar trends indicating that they are earlier than at least one phase of folding. Therefore on the basis of style and direction of plunge these are equated with the earliest north-east phase of folding.

One of the factors on which the establishment of the age relations of these folds rests is the presence of north-east trending pegmatite veins seen to be cut by Lewisian dykes at Leenish, north of Brevig Bay. It is unfortunate, however, that the number of these examples exposed is small. Here an 8 inch, 30^{o} striking pegmatite vein is cut by two sets of cross cutting Lewisian dykes and a 60^{o} trending, 2 inch pegmatite vein (fig. VIII-4; cf. VII-14). The relative size of these veins and their relationships to the dykes seemed worthy of further consideration. Certainly on the basis of size one would expect that if the 30^{o} and 60^{o} trending pegmatites were related in time, the 8 inch pegmatite vein rather than the 2 inch pegmatite vein should cut other earlier structures. But since it is the narrower vein which cuts the dykes it seems reasonable to conclude that the 2 inch one with the 60^{o} trend is later than that trending 30^{o}, especially as some of the largest north-east trending veins are cut by dykes of Phase 7. The relation between the earlier dyke and the first (8 inch) pegmatite vein is not seen. North-east plunging folds of the late F_5 fold period trend between 50^{o} and 70^{o}.

The above relationships might be taken to imply that Phase 5 deformation was interrupted by, or was contemporaneous with dyke intrusion - provided of course that it is accepted that the north-east injection of quartzo-feldspathic material derived from anatexis was parallel to axial planes of the folds produced during this deformation. Intrusion of dykes certainly took place between the two pegmatite injections described and it must have taken place at such time when tension fractures were open in a markedly different direction from those in existence at the time of the injection of the two north-east pegmatite veins. The dykes strike approximately north, the first dips gently east and the later one steeply east. For such events to have taken place there must have been a distinct pause in the operation of the forces responsible for the north-east folding between the time of the injection of the first (8 inch) pegmatite vein and the second dyke at least before renewed deformation, concurrent anatexis and subsequent pegmatite vein injection took place. The necessity for this train of events depends on the assumption that dyke intrusion took place under non-orogenic conditions, but in any case tension fractures must have been in existence before their emplacement. Dyke emplacement may, however, have been along ac tension fractures related to a second spasm of north-east (F_1) folding and the second pegmatite vein injection would then have taken place during subsequent release of compression perpendicular to the fold axial direction at the conclusion of the F_1 folding. But the distinct possibility that the second pegmatite vein might be related to the latest north-east fold phase or to an oblique fracture related in some other way to a later and different period of folding cannot be disregarded. It is not thought, however, that the final comparatively mild north-east folding was accompanied by appreciable migmatisation and pegmatite vein intrusion, and cross cutting relationships with various Lewisian dykes of large veins like the coarse 50° trending quartzo-feldspathic vein (fig. XIX-1) with a centre of white quartz at Leenish used as evidence for the separation of intrusives of Phase 4 from those of Phase 7, provide strong proof of the existence of more than one period of dyke intrusion.

The amount of decisive evidence in Phase 5 is thus very slight, although other less positive factors tend to corroborate this. For example the sporadic distribution of the north-east fold and the fact that it never appears to be accompanied by related penetrative structures like lineation[3] or close spaced planar features and fractures suggestive of axial planar structure as in the case of some of the later symmetrical, open type of north-east folds.

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3. Sandblasted rocks exposed above the beach on the island of Mingulay to the south show a strong lineation, due to cylindrical rods of pyroxene, hornblende and feldspar, which plunges towards approximately 20°. (See Addendum p. 141).

IX. BOUDINAGE AND AGMATITE FORMATION

A. Boudinage

Field evidence suggests that during the period following the injection of the earlier series of basic intrusives the tectonic environment of the gneisses was such as to favour the formation of most of the boudinage exposed at present in this field. Boudinage and the development of agmatite is grouped under the sixth phase of the tectonic history outlined on page 40.

A number of examples have been seen of types of boudins genetically distinct from those to be discussed in the present section. These include lenticular remnants of hornblende granulites similar to the latest dykes of phase 7c, exposed below the Thrust at Bruernish and on the north-east coast of Orosay, Traigh Mhor (fig. IX-1; map I). These are disposed in lines of disconnected lenses and this suggests that they are the products of intense shearing stress slightly oblique to their length. The separation into lenses has thus been accompanied by rotation and the forces responsible for their deformation may have been related to early thrusting. The deformation responsible for forming these lenses is distinct from that producing rotation of already formed boudins like those outcropping south of Brevig (fig. IX-2) and at Bagh nan Clach (fig. IX-3). Yet another kind of boudinage results from rotation following shear of small quartzo-feldspathic veins. Small examples of these structures are exposed at the north end of Bagh nan Clach (fig. XIX-5). The boudins to be described in this section from north of Bagh nan Clach and from other places in the field are considered to have formed in response to stresses of a distinctly different nature.

Strictly speaking, all those structures should be termed tectonic inclusions rather than boudins since they have not been seen in three dimensions, but their cross sectional form is sufficiently like that of the type boudins from Bastogne (Lohest, Stanier and Fourmarier, 1909) to warrant their being described as such. Their relative dimensions in cross section vary considerably, some being several times greater in width than in thickness (fig. IX-5) while others are approximately equal in thickness and width (fig. IX-6). None have been so completely exposed as to show the relationship between length, width and thickness. The edges parallel to the foliation are sometimes approximately planar (fig. IX-5) but more usually they are gently waved or corrugated (figs. IX-4, 6). Although most cases show modification of termination at the separation (fig. IX-8) with rounding off of the corners (figs. IX-4, 5) there are some examples which exhibit almost rectangular truncation (fig. IX-2). Only seldom do boudins belonging to this early generation have a cross sectional form pinched out in the style shown by the left end of the boudin to the right of the hammer in figure IX-4. This lenticular form by contrast is typical of the sheared dykes already noted from Orosay and Bruernish (map I).

All boudins show signs of incipient septation by migmatite. The least affected are veined from end to end parallel to the surrounding foliation (fig. IX-5) and nearly all exhibit spalling of thin outer layers which may have disintegrated and floated out into the surrounding migmatite (fig. IX-2). Adjacent to quartzo-feldspathic infiltrations the normally dark grey amphibolite comprising the boudins is usually darkened (fig. IX-2) in the manner described in section XIX. Advanced stages in attack during anatexis has resulted in spalling of shells, of which there may be several, from the margins (figs. IX-2, 6) and break-down of the centres (figs. IX-4, 5, 6) to agmatite.

In many cases the orientation of the separation parallel to b of the boudinage suggests a close relationship with F_4 folding where B trends parallel to 100°. Nevertheless, although some F_4 folds are shear folds or folds accentuated by shear (fig. XIV-7), most appear to be generated by flexure (fig. XIV-5, 6) and the stress patterns necessary to produce flexural folds and boudinage with b parallel would have to be directly opposed. Maximum compression (P_{max}) in the case of the folds would have been parallel to the foliation, whereas in the case of the boudinage, P_{max} would have been perpendicular to the foliation (Ramberg, 1956, p. 516).

Furthermore, the boudinage does not display the same constancy of orientation as the 100° trending folds and this supports the fact that it must be a comparatively early formed structure and not one resulting from a stress field (or fields) active during the later phases of the tectonic chronology which has been determined here.

The overall similarity in appearance of boudins with different attitudes in widely separated localities suggests that they have the same tectonic history. In the absence of radiometric age data it is inferred therefore, that they are of the same age. Boudinage in south-west Barra is subhorizontal, apparently plunging down dip in foliation dipping at approximately 10° to the west (fig. IX-4), that at Scurrival lies in foliation which dips steeply north-east at 60° (fig. IX-5), a further example just south of Brevig near the south-east coast lies in almost vertical foliation, dipping at 75° to the east (fig. IX-2) and other examples near Ard na Gregaid on the south-west coast (fig. IX-6) at Bagh nan Clach (fig. IX-7) and on the east coast at Scurrival (fig. XII-29) appear to plunge gently northwards. These examples indicate fairly conclusively that boudinage occurred at a time when the foliation at the various localities noted held attitudes and relative positions vastly different from those occupied at present (fig. IX-8), provided it is accepted that the stress field generating the structures was regional in scale and constant in orientation. If similar appearance can be equated with similar tectonic histories then it seems reasonable to postulate formation of the cases quoted as a result of the same stress system. They must then have developed prior to F_2 folding which appears to have produced the greatest major reorientation of foliation, and there is good field evidence to show that these structures were in existence before the F_2 phase in that small boudins on the flanks of minor folds of this generation show rotation, and even squeezing together (movements directly opposed to those accompanying their genesis), compatible with movement of the kind associated with the genesis of F_2 folds (figs. XII-

27, 28, 30). Whether or not tectonic conditions responsible for boudinage obtained during F_1 folding is a debatable point, but at present its development is grouped under Phase 6, being later than Phase 4 and earlier than Phase 8 and probably earlier than Phase 7.

Assuming approximately parallelism of the general strike, as is the case at Brevig and elsewhere on the east coast, after F_1 folding and prior to F_2 folding it is possible to postulate a stress field producing compression subnormal to the foliation - perhaps as a result of rotation of the field responsible for the generation of F_1 folds. Very little is known about the nature of the F_1 folding but from the fact that folds are generally small it seems likely that the gneiss responded semi-plastically to deformation at that time and plasticity of the quartzo-feldspathic layers was probably the result of the onset of migmatisation at depth. It is thought that conditions favourable for boudin formation obtained at moderate depth where basic bands were still rigid enough to fracture under the effects of lateral tension while quartzo-feldspathic gneiss on the other hand had become sufficiently plastic to bend in response to stress. At greater depth increased plasticity and more vigorous attack of basic gneisses during anatexis resulted in the formation of agmatites. Towards the close of the F_1 phase then, conditions would have been ripe for boudin formation, with migma still available locally and from deep seated anatexis to fill the tension fractures developed in basic bands in the gneiss. It is tempting to carry this speculation farther and suggest that with release of compressive stress with the onset of non-orogenic conditions, tension fractures subparallel to the foliation provided paths for basic magma which solidified to form the dykes representing the next phase of igneous activity, Phase 7 - in the chronology.

Corrugations clearly related to the boudinage (figs. IX-4, 5) are thought to have formed at this time under the same conditions. Their development is discussed under section XIV, p. 142.

B. Agmatite Formation

Before the final group of Lewisian dykes was emplaced some parts of the region were subjected to intense anatexis and brecciation of the basic gneisses which appear to have been attacked and partially "digested" by the migma generated from quartzo-feldspathic gneisses (fig. XIX-11). During this phase agmatites were formed. Some of these were replacement agmatites in which the original orientation of the relict basic bands is still more or less preserved (figs. IX-9, 10, 11, XIX-19) while in others the orientation of the original foliation clearly indicates that relative movement of the enclaves in the agmatite has taken place (fig. XIX-13). Basic amphibolite dykes probably equivalent to intrusives of phase 4b, have, in areas of intense migmatisation, been fractured and penetrated by quartzo-feldspathic material, but because of their high resistance to the effects of the migma have preserved their original parallel-sideness, and to some extent, their orientation (fig. XIX-18).

The hornblende biotite balls in feldspathic pegmatite at Leenish (fig. IX-12) and the coarse hornblende pegmatites of Ersary (fig. XIX-3), Leenish, and south Bruernish (fig. IX-13) are probably the end products of extreme anatexis of this phase.

The age of agmatites of this type can be defined within certain close limits from the following evidence. The composition of the agmatite enclaves agrees closely with that of dykes and intrusives of phase 4c and the agmatites themselves are cut by later intrusives of light grey type which are earlier than the pyroxene granulites of phase 7c and are probably equivalent to phase 7a. The grey dyke in the left hand side of the photograph of the breccia at Rudha Mor (fig. XIX-16) is clearly later than the agmatite of basic gneiss through which it can be seen to cut. The agmatite on the south coast of Bruernish (fig. XIX-13) is intersected by a fine lineation trending 100° and by quartzo-feldspathic pegmatite veins trending 160° corrugated slightly by 100° F_4 folds. The agmatite is therefore older than the F_4 folding of phase 11 and probably older then than F_3.

The anatexis and accompanying migmatisation and brecciation appear therefore to be of approximately the same age as that deduced for the boudinage. If this is so it seems probable that the agmatites are the products at deeper levels of attack under the same anatectic conditions which resulted in injection of migma into boudins forming, or formed, at higher levels in the crust.

In as much as it seems a reasonable assumption that anatexis and migmatisation has accompanied all fold phases at some levels (hence the derived quartzo-feldspathic pegmatite veins parallel to axial planar directions) it is very likely that some of the agmatites exposed in the field may be the products of different periods of anatexis but in the absence of radiometric ages (Holmes 1963, p. xxi) there seems little point in attempting further pursuit of this argument. There is also the possibility that pegmatite veins could be injected into axial planes of folds of any of the earlier generations but this contingency is less likely because earlier fractures would have healed during subsequent intervening orogenies.

X. LATER INTRUSIVES OF THE LEENISH COMPLEX

A. Second Series of Leonish Intrusives

1. Early Phase.

Lewisian dykes of Phase 7 which cut north-east trending pegmatite veins believed to be related to axial planes of the earlier 30° plunging F_1 fold directions outcrop fairly frequently, particularly to the east of the main Hebridean Thrust. By far the most common occurrence is in the area including the south-eastern tip of Leonish, north to Loch Obe in the neighbourhood of Balnabodach. A few remnants of these dykes have been mapped below the Thrust at Bruernish and Orosay, Traigh Mhor but all of these are sheared out into lenses and show obvious effects of strong deformation, perhaps in consequence to thrusting.

Included in this phase are the hornblende granulites described by Jehu and Craig (1923, p. 467).

Intrusives of phase 7a are of acid to intermediate composition. They are biotite gneisses and form light coloured distinct dyke-like bodies showing clear cross cutting relations with the foliation and earlier intrusives. Angular discordance of as much as 40° exists between these dykes and the foliation in places.

The dykes of which specimens 736 and 752 are typical examples, are narrow (less than a foot wide) and almost white, and weather to a distinct rusty colour. They are lepidoblastic, with biotite the only important dark mineral present, and are somewhat similar to the biotite dykes of phase 4 but show a very much weaker preferred orientation of the mica flakes. Quartz and feldspar comprise 90 to 95 per cent of the rock, brown biotite up to 5 per cent, dark green hornblende 2 per cent opaque (magnetite) 1 per cent and apatite 1 per cent (fig. X-1).

2. Middle Phase.

Phase 7b intrusives which include specimens 721, 723, 729, 740, are biotite-rich basic dykes. They are dark grey in colour and their intrusive nature can be clearly seen in the field. They range from 4 inches to 4 feet in thickness and display obvious crosscutting relationships with the foliation and other dykes. In thin section this gneiss is seen to have nematoblastic (Harker, 1950, p. 201) to lepidoblastic texture with moderate preferred orientation of biotite and hornblende. It contains the following proportions of minerals. Twinned plagioclase (andesine-labradorite) 50 to 60 per cent, dark green hornblende 20 to 35 per cent, brown biotite 15 to 20 per cent, opaque minerals 2 to 3 per cent and apatite up to 2 per cent (fig. X-2).

3. Late Phase.

Dark, clear cut hornblende gneissic dykes up to 10 and 20 feet wide with nematoblastic to granoblastic texture are thought to be later than those of Phase 7b. These basic dykes of Phase 7c have more nearly equal grain size with only slight evidence of preferred orientation which in this case is in the form of ovoid mineral aggregates expressed in fine banding. The bands are defined by variation in the proportion of the constituent minerals. Specimens 719 and 744 have the following mineralogy. Twinned plagioclase (andesine) about 50 per cent, hornblende 35 per cent green clino-pyroxene 15 per cent (fig. X-3). Some of the interfoliated basic hornblendic bands in the gneiss elsewhere have similar composition and probably represent concordant intrusives of the same age.

The most recent dykes of this phase are usually strikingly different in appearance from the enclosing gneisses and generally preserve original intrusive features like branching and difference in grain size at the margins. They show marked angular discordance with the foliation, although in most cases this does not exceed 40° and is commonly very much less, except on the south-west shore of Loch Obe and west of Balnabodach where dykes cut the foliation at nearly 90°. In size they range from about 8 inches (fig. X-4) to 50 yards (figs. X-5, XI-2) across although in some cases minor veinlets only 2 inches wide form distinct discordant bodies (fig. X-6). Cross-cutting relationships between individual dykes of even these, the latest recognizable intrusives, have been recognized in a number of instances (fig. VII-14). As already discussed (pp. 52-69) there is good evidence to show that they were emplaced with attitudes relative to foliation very close to those displayed at present.

Dykes of this age include the pyroxene granulites described by Jehu and Craig (1923, p. 428).

In hand specimen the younger dykes range from almost bluish dark grey to slightly brown-weathering, lighter grey in the case of the older rocks and in this respect superficially resemble many of the post Lewisian intrusives. The texture varies a little with size and age also, being granoblastic in the larger and younger intrusives whereas the older and narrower dykes tend towards lepidoblastic and nematoblastic texture. In the centre of some of the larger bodies there is a tendency for some minerals like garnet to group in small ovoid lenses measuring about 2 x 3 millimetres in cross section and these are aligned parallel to the length of the dyke. In the same direction there is often a faint banding due to changes in proportion of the constituent minerals. The coarser textures usually result in the rock with a lighter colour, often brown to buff, in hand specimen.

The appearance of thin sections viewed in reflected and transmitted light without the aid of a microscope strongly suggests ophitic texture and this shows up also in microphotographs (fig. X-7). However, the appearance under the microscope using even low magnification shows that complete recrystallisation has taken place and that the relict textures referred to comprise equant grains arranged in branching groups simulating ophitic texture (fig. X-8). None of the examples examined of even those, the youngest of the Lewisian dykes, was seen to contain relict microscopic igneous texture.

Examination of thin sections of rock specimens representing all the dykes collected, and comparison of their mineralogy failed to show any consistent and regular distribution in the field which would suggest that variation in mineral assemblages from dyke to dyke is due to regular variation in metamorphic grade. It has been concluded that the mineral assemblages in the dykes depend on four factors:- 1) original composition, 2) age, 3) size of bodies, 4) whether or not they are cross cut by pegmatite veins. It is not impossible, and indeed it is very likely that a fifth factor, that of increasing or decreasing metamorphic grade from one part of the field to another, has influenced the mineralogy but any such variation in grade, if it exists at all, must be of very irregular distribution or else the other four factors have masked any regular gradation that might have existed previously. The texture of the younger large dykes is saccharoidal to interlobate granoblastic (Berthelsen, 1960, p. 24) and the mineralogy as shown in specimens 603, 604, 614, 673, 733 classifies them as pyroxene, and hornblende granulites. Twinned plagioclase (andesine) comprises 50 to 60 per cent of the rock, hypersthene (pleochroic) 15 to 20 per cent, green clinopyroxene 5 to 10 per cent, garnet up to 20 per cent, hornblende up to 20 per cent and opaques 5 per cent (fig. X-9). This changes with increase in mineral alignment and incoming of hornblende and (? later) brown biotite which gradually increase, as a rule towards the margin, where the rock becomes a hornblende granulite. This regular type of variation does not always hold and at Rudha Liath for example, a dyke 50 yards wide of hornblende granulite composition is in contact on its north-eastern margin with pyroxene granulite country rocks. The possibility that this contact may be tectonic is ruled out for the following reasons. There is no mechanical evidence of shear at the margin to be seen either in the field or in thin section. In the field small tongues can be seen to branch off the main dyke and taper out in the adjacent country rock. There is no indication of an increased proportion of minerals characteristic of a lower metamorphic grade at the contact and in fact the margin is marked by a thin layer of fine, equant hypersthene granules (specimen 668, fig. X-10).

With increasing age and decrease in size the disappearance of hypersthene and appearance of hornblende is usually the first marked change. The occurrence of garnet and green clinopyroxene on the other hand seems to bear no fixed relation to either the age or size of the intrusive, since either or both of these minerals can occur in the highest grade pyroxene granulites or in narrow amphibolite bodies (figs. X-11, 12), and their occurrence appears to be a consequence of original composition. In general there is a striking lack of reaction structures, like keliphite rims, throughout the field.

XI. PYROXENE GRANULITE REGIONAL METAMORPHISM

Detailed investigation of the metamorphic petrology of the gneisses lies beyond the scope of the present research but it was felt that an examination of the distribution of rocks of different metamorphic grade would be of assistance in considering the general structure. (The onset of this period of regional metamorphism is referred to in Phase 8 of the tectonic history). To this end the mineral assemblages of 280 thin sections were determined, with particular attention being paid to those of the basic intrusives. The variation in distribution of the different facies was marked on a map to determine whether or not any pattern exists, (fig. XI-1). In addition, specimens were selected from the centre and margins at intervals along one of the larger of the latest dykes at Rudha Liath in order to see if any regular and consistent variation in mineral assemblage and metamorphic grade could be detected (fig. XI-2). Finally a comparison was made between the width and metamorphic grade of several basic dykes (Table 6).

The areal distribution of different facies, determined from mineral assemblages using criteria from Fyfe, Turner and Verhoogen (1958), suggests that the areas of highest metamorphic grade lie on a slightly curved narrow zone trending north-east from the coast west of Rudha Charnain, through the base of Leenish to a point just east of a small loch near the entrance to Loch Obe. Here the line appears to be offset to the south-east by a possible north-north-west trending fault parallel to Loch Obe entrance. East and west of this narrow zone the metamorphic grade of specimens examined, including both foliated gneiss and intrusives, appears to decrease irregularly. The erratic distribution of isograd lines is considered to be due to the fact that the zone is tangential to an elongated arched pyroxene granulite isograd surface which has been exposed at this level. The fact that hornblende and pyroxene coexist with very rare evidence of inter-replacement suggests that conditions were such that both minerals were in equilibrium during metamorphism. It is thought too that many of the latest of the Lewisian dykes are of higher grade only because they have preserved pyroxene granulite assemblages in consequence to their comparative resistance to retrogressive metamorphism brought about by migmatisation whereas older basic bodies had been reduced in size by anatexis and were more susceptible to retrogressive metamorphic effects. Pyroxene granulite country rock adjacent to the Rudha Liath dyke where it is exposed at the coast east of Balnabodach is possibly a segment of gneiss protected from lateral and vertical migmatisation and retrogressive changes by surrounding impervious basic intrusives. Were it not for the fact that the exposure dips under the sea at this point, the metamorphic grade of the country rock would in all probability be seen to fall further eastwards away from the protective "shadow" of the basic dyke (fig. XI-3). It is thought that the migmatising fronts moved laterally from the south-west, as well as upwards, in this area since a similar relationship of higher grade gneiss to the east of the dyke is suggested further south near Rudha Liath (fig. XI-2).

Table 6. Metamorphic grade of Lewisian dykes in relation to their width.

Approximate Width	Country Rock	Margin	Metamorphic Grade Centre	Margin	Country Rock
300 feet			P. 696	H. 665	P. 665
250 feet	H.A.	H.A.	H.A.	H.	P.A.
30 feet		A. 735	P.H. 733, 734		
30 feet			H. 728		
20 feet			H. 743		
20 feet			H. 744		
10 feet			H. 719		
? feet			A. 724		
4 feet			A. 722		
4 feet			H.A. 738		
4 feet			A. 740		
3 feet			A. 754		
2 feet			H.A. 741		
2 feet	H.A.	H.A.	H.A. 739		
2 feet			H.A. 738		
18 inches			A. 732		
18 inches			A. 742		
18 inches			H.A. 731		
18 inches			A. 729		
12 inches			A. 721		
12 inches			A. 726		
12 inches			A. 727		
12 inches			A. 730		
12 inches			A. 753		
12 inches			A. 737		
12 inches			H.A. 747		
8 inches			A. 736		
8 inches			H. 745		
6 inches			H.A. 746		
4 inches			A. 752		
X			A. 748		
X			A. 749		
X			H. 633		
X			H. 634		
X			H. 637		
X			H. 639		
X			H. 649		
X			A. 650		
X			A. 651		

P = Pyroxene granulite grade.
H = Hornblende granulite grade.
A = Amphibolite grade
Numbers listed are specimen numbers.

Whether or not in this case it is necessary to advocate intrusion of these dykes under granulite facies conditions to account for their textural and mineralogical features as suggested for similar dykes in south-west Norway by Antun (1963), or under conditions of high temperature and pressure as proposed by O'Hara (1961) for the Scourie dyke, is doubtful. But in any case considerations of this nature lie strictly outside the scope of the present work. It is suggested, on textural evidence,(figs. X-7, 8) that the dykes of the present field crystallized with normal igneous, ophitic textures and were later metamorphosed to pyroxene granulites.

Comparison between widths of about 40 dykes and metamorphic grade failed to reveal any distinct definite correlation. Admittedly the largest dykes like those at Balnabodach all yielded some specimens of the highest pyroxene granulite grade but from them also specimens of almandine amphibolite grade were collected. Furthermore, one of the finest examples seen of a pyroxene granulite came from a dyke only 20 feet wide exposed in a small quarry at Skallary. Specimens from this dyke contained hypersthene and clinopyroxene in equal amount with only a trace of hornblende. All pyroxene granulite specimens come from dykes 20 feet wide and over, ranging up to 300 feet and more across on the outcrop. Since they dip steeply, at usually more than 60°, widths and thicknesses are of the same order. Larger sized metabasite bodies from Phase 4a of possibly lower grade exist but their presence can readily be accounted for by consideration of the fact that these intrusives underwent lengthy periods of deformation and brecciation before metamorphism. They were thus readily susceptible to attack and downgrading during subsequent migmatisation. Hornblende granulites come from dykes ranging between 8 inches and 50 feet in width. None of the dykes seen of the lower almandine amphibolite facies exceed 4 feet in thickness. This grouping might serve to suggest that a relationship exists here between dyke thickness and metamorphic grade in a region where retrogressive metamorphism of the country rock has begun to affect the basic intrusives. But this concept is somewhat difficult to reconcile with the fact that in some cases dykes with lower grade hornblende granulite margins are in unsheared contact with foliated gneiss of high grade pyroxene granulite facies. On the other hand there appears to be a fairly consistent relationship between metamorphic grade and dykes affected by migmatisation and intrusion by quartzo-feldspathic pegmatite veins. This is well shown in the 30 feet wide granulite dyke at the south-east tip of Leenish which is of hornblende pyroxene granulite grade at the centre. At the contact with thin pegmatite veins the centre of the dyke is downgraded to almandine amphibolite with a gradual decrease along the vein to the dyke margin. Adjacent to very thin pegmatite veins which range from a quarter, to one inch in thickness in the same dyke, the gneiss is darkened in zones up to 2 inches wide, in which increase in size of small red garnets has taken place (fig. XIX-2).

The large dyke striking north-north-west from Rudha Liath outcrops for about a mile from the coast to the edge of the overthrust sheet but because of offsetting due to faulting is exposed for much of its length along the shore (map I). At its southern end the dyke was sampled at the centre and margins at three localities along a length of 600 yards. Specimens of the adjacent country rock at these places were collected also. A total of 16 specimens collected and sectioned for examination showed that there is no regular or consistent variation across the dyke or from centre to margins. At the southern extremity on the shore, both the dyke and the enclosing gneiss at the contacts are of almandine amphibolite grade. At the second locality 400 yards north-west, the metamorphic grade ranged from low almandine amphibolite at the western contact to hornblende granulite at the centre, back to amphibolite at the east margin and then to pyroxene granulite in the adjacent country rock. At the north end the dyke bifurcates and specimens were examined from the north-west branch. From the western contact in the gneiss across the dyke to the eastern gneiss, the rock grades from upper hornblende amphibolite facies to lower amphibolite facies. Exposure in this area is insufficiently good to allow a detailed investigation of this variation and in fact prevented sampling at equal intervals in the present instance. Nevertheless, at its southern end the dyke is very well exposed, and here it can be seen that the grade from one side to the other remains the same. It is therefore likely that the facies variation exhibited by the intrusive as a whole is not due to sampling error and possibly reflects different relative rates of movement of the metamorphic front, and or later migmatisation fronts, because of differences in permeability of foliated gneiss and intrusive (fig. XI-3).

Determination of the position in the proposed sequence of this period of metamorphism is difficult. There are two main lines of evidence defining an upper and a lower age limit. The fact that the dykes contain mineral assemblages of high metamorphic grade and relict igneous texture indicates they were emplaced prior to metamorphism. The marked difference in coarseness of texture, but not necessarily in grain size, between the margins and centres of the latest dykes suggests that they were emplaced in comparatively cool country rocks; the implication being that the relict fine marginal texture is indicative of rapid cooling near the contact and this suggests that intrusion took place well in advance of rising geothermal gradients heralding the approach of the advancing metamorphic front. The second line of evidence stems from the lowering of metamorphic grade with migmatisation. On the continued acceptance of the fact that different trends of quartzo-feldspathic pegmatite veins are associated with distinct periods of folding, it seems that metamorphism antedates the F_2 fold period of Phase 10 with which are associated south-east trending pegmatite veins. This is because the metamorphic grade of the dykes where these are adjacent to pegmatite veins is distinctly lower than elsewhere, suggesting retrogression of grade during vein injection. From this it is concluded that following the intrusion of the second group of dykes of the Leenish Complex and prior to F_2 folding the metamorphic grade of the gneiss was raised in some areas as high as the pyroxene granulite facies. Anatexis associated with succeeding fold phases progressively reduced the metamorphic grade of all but the most impervious, basic gneisses.

It is possible that there were other periods during which the metamorphic grade rose but conclusive evidence for their existence has not so far been found. Radiometric ages determined from different metamorphic minerals along the lines suggested by recent Russian work may serve to provide this evidence. (Potassium:argon ages from pyroxenes are considered in this work to represent the date of progressive regional metamorphism, and ages from amphiboles and biotites the dates related to retrogressive metamorphism. Gerling, et al., 1964).

XII. SECOND FOLD PERIOD. F_2

A. General Field Relationships

Following the dyke intrusions just described, the next period of folding distinguishable as a separate phase of deformation produced fold structures of a very distinctive style which are recognizable throughout the field. The largest of all the folds mapped during the investigation were formed during this orogeny, the ninth event listed in the tectonic chronology outlined in page 40 . In the field the folds appear distinctly asymmetrical in style with hinge lines which trend east-south-east. They have an axial plunge to the north-north-west (fig. XII-1) which is not as a rule, easily determined and in most exposures is difficult to recognize at all. The largest structure identified as belonging to this generation is the fold which forms the small peninsular at Scurrival north of Eoligarry and is the only structure which has been determined macroscopically. It has a wavelength of approximately half a mile and, in common with mesoscopic folds of the same age, is characterised by an easily discernible, regular axial planar strike of approximately 120° (fig. XII-2).

Prior to this phase of folding, or at its onset, there appears to have been a period of recrystallization during which small needles of black hornblende were formed. These needles are now so disposed as to show good alignment on one limb of the folds of this generation but not on the other and this suggests a reorientation during F_2 folding of previously existing minerals.

The macroscopic Scurrival structure comprises three limbs of a gently north plunging, similar fold which forms an outcrop pattern comparable in shape to a reversed Z. The northern limb strikes approximately east and dips gently north. The central limb strikes south-east, and is overturned at the north end where it dips steeply to the east. At the southern end the foliation dips to the west before the strike swings round to the west on the southern limb where the dip is once more northerly.

The axis of the Scurrival fold was found macroscopically to plunge at approximately 25° to 345° (fig. XII-11). The nose of the fold at the hinge between the north and central limbs forms Scurrival Point. From the map (map I), it can be seen that the foliation on the north limb is approximately parallel to the shore which here strikes gently more or less parallel to the dip. At the hinge the foliation is sharply overturned and again follows the shore, which is steeper here because of the inland-directed dip. Further south at Bagh nan Clach, the foliation stands vertical and then dips to the west before curving out to sea parallel to the shore to form the small promintory at the south end of the bay. The continuity between the central and southern limbs of the structure has been destroyed by the emplacement of a large south-east striking post-Lewisian quartz dolerite dyke along a fracture which transects the foliation close to the hinge line. Smaller mesoscopic folds of the same style occur on the limbs of the major structure at various localities in this part of the field (fig. XII-1).

The gneiss on the coast south-west of Barra at Ard na Gregaid has been folded by a similar but very much smaller structure, with a steeply dipping south-striking limb and a more gently north-north-east dipping limb (fig. XII-3). Although on a much lower order of scale, with a wavelength of probably only 10 or 15 yards, this structure nevertheless possesses the south-east fold axial planar strike characteristic of this style of deformation.

Step folds seen in both horizontal and vertical sections are two other distinctive outcrop features resulting from folding of this style. Step or monoclinal folding is well displayed in vertical joint faces (figs. XII-23, 24, 28) particularly in the north of Barra at Scurrival (fig. IX-7) and in horizontal section on the ground on Ard Mhor (fig. XII-15; map I) where the axial plane is sub-parallel to the general strike of the foliation, here approximately 120°. As a rule the form of the fold pattern appearing on the maps, especially those on a scale of 1:2,500, is the result of folding about the F_2 northerly plunging axis (maps II, V, VII, etc). Examples of this can be seen at the north end of Orosay, Traigh Mhor where the remnants of a late Lewisian dyke now represented by a series of lenses appears to be folded on the same style (map I). In some parts of the field smaller scale mesoscopic folds may show plunge in the reverse direction, and folds of this type outcrop on the northern shore of Castlebay.

Here and there the axial planar trend of folds of this period can be seen to curve, apparently in response to warping about later fold axes, as is the case on the shore at the west end of Halaman Bay (fig. XII-4). This effect of curvature of trend of the axial surface of smaller folds of this generation is also clearly displayed on the west coast near Scurrival Point. At this locality (map II) the characteristically asymmetrical ground plan of the east-north-east and south-south-east striking limbs is well shown as is the trend of the hinges of the individual folds which varies between approximately 110° and 120°. The generally lobate plan of the northern fold hinges of the major structure is accentuated by the curved nature of the shore on the flanks of Ben Scurrival near the summit, and the curvature of the axial planar trend of the main structure is similarly accentuated by the effects of topography. The southern hinges are not exposed. The north-dipping limbs of the structure also show slight, but distinct, curvature, being concave to the north, and this further suggests later warping about an axis with a north-easterly trend.

Apart from the macroscopic Scurrival fold most of the structures recognized as belonging to this phase range in size from that of the Ard na Gregaid fold down to folds with wavelengths of only a few inches. Good examples of the form and style of very small folds of this generation can be seen on the south-east coast at Traigh Mhor (fig. XII-28) and in the hillside near the school at Eoligarry (figs. XII-21, 25). In addition, the attitudes of foliation on the limbs of mesoscopic folds of this style occurring below the thrust at Bruernish on being plotted on a β - diagram showed an axial plunge of approximately 15° to 350°.

B. Petrography of the Scurrival Gneisses

Detailed mapping on the scale of 1:2,500 of the structure in the vicinity of the shore at Bagh nan Clach (map II) was possible only because of the presence of marker horizons of persistent inter-foliated quartzo-feldspathic gneisses and amphibolites. These include a number of bands, distinctive by their garnet content, which could be traced even when the exposure (normally excellent in this particular area) becomes intermittent. The quartzo-feldspathic gneisses include some cream and white varieties with a distinctive rusty brown weathering which contain pale purple garnets instead of the more usual deep red brown variety normally to be found in the gneisses of the complex. In appearance the more acid gneisses are very closely similar to some of the gneisses on Rodil considered to be paragneisses in South Harris by Jehu and Craig (1927) and to the paragneisses of Tiree (Bailey, et al., 1923) although graphite has not been found in any of the Bagh nan Clach gneisses. The basic, and the more quartzo-feldspathic layers have been distinguished as light and dark gneiss on the map.

The petrography of some representative specimens is as follows,

1. Light Gneisses.

The gneiss of specimen 645 forms a moderately thick and distinctive brown buff weathering layer on the limbs of a narrower, north-plunging antiform (map II, fig. XII-5). In hand specimen it is a fine grained, grey and white banded gneiss with a pale pink tinge imparted by the presence of numerous pale pink to lilac coloured, subhedral to euhedral garnets ranging from pin-head size to a quarter of an inch in diameter.

In thin section this has a lepidoblastic to granoblastic texture and comprises; about 25 to 30 per cent reddish brown biotite in short stubby flakes; pale pink garnets scattered either singly or in groups with sometimes a few small pools of quartz enclosed poecilo-blastically, 20 per cent; strained quartz grains, about 25 per cent; slightly sericitized andesine, 25 per cent; occasionally apatite occurs as elongated grains and with opaque minerals comprises less than 2 per cent.

Specimen 464 is a distinctive, light brown weathering, fine-grained white to grey gneiss with foliation defined by alignment of thin aggregates of biotite.

In thin section the rock is interlobate granoblastic in texture with irregular shreds of pale greenish brown biotite containing small pleochroic haloes around minute ? zircons making up about 20 per cent of the rock; strained quartz constitutes approximately 30 per cent, twinned clear andesine about 40 per cent; irregular remnants of large kyanites comprise 5 per cent, and very small anhedral pink garnets (almandine) 1 to 2 per cent. There is a little microcline present. Apatite granules and opaques (magnetite) make up about 3 per cent.

Specimen 463 is similar but coarser, containing strained biotite and altered feldspar.

Specimen 468 comes from a band of fine grained, brown weathering, almost white gneiss peppered with scattered small biotite flakes, which is reminiscent of a metamorphosed aplite.

In thin section it is seen to have an interlobate granoblastic texture. A few scattered shreds of red-brown biotite showing slight strain comprise almost 10 per cent of the rock, slightly dusty strained quartz makes up 40 per cent and slightly altered oligoclase, 45 per cent.

Specimen 462 comes from a creamy grey gneiss containing small brownish red garnets.

Thin sections show a lepidoblastic to granoblastic texture and the rock is made up as follows; reddish brown biotite flakes, 20 per cent; pale green to colourless lamella twinned amphibole (? cummingtonite), 10 per cent; microcline and strongly clouded and sericitized feldspar (? orthoclase), 30 per cent; strained quartz grains, 25 per cent; slightly clouded oligoclase, 15 per cent; pink anhedral garnets (almandine) about 2 per cent; elongate apatite granules 1 per cent; opaque (magnetite) 1 per cent.

2. Dark Gneisses.

The following are examples of dark, basic gneisses. The brownish red garnets have a refractive index of about 1.79 corresponding to almandine.

Specimen 466 is a dark grey to greenish black gneiss in hand specimen with a more or less nematoblastic texture.

In thin section the rock displays nematoblastic to granoblastic texture, containing dark green hornblende which encloses small blebs of quartz poeciloblastically, and subhedral garnets. Hornblende which comprises 70 per cent of the whole occasionally displays simple twinning and is sometimes rust stained; pink subhedral almandine garnets heavily chloritized along cracks, and almost completely replaced in some cases, make up 10 per cent; clouded feldspar (? orthoclase) flecked with clinozoisite comprises 2 per cent; small lobate strained quartz grains amount to 10 per cent; twinned andesine 10 per cent; opaque minerals (magnetite) in irregular patches and rods about 1 per cent. The whole is transected by thin epidote veins.

Specimen 465 is similar but coarser and more leucocratic with larger, $\frac{1}{4}$ - inch diameter, poeciloblastic pink garnet porphyroblasts.

Specimen 460 is similar to, but lighter in colour in hand specimen than, 466.

In thin section the rock is nematoblastic to granoblastic saccharoidal in texture comprising 30 per cent greenish brown hornblende; 25 to 30 per cent pale green clinopyroxene flecked with hornblende flakes; quartz is rare and confined to very small circular blebs enclosed in ferromagnesians and feldspars; feldspar is clear twinned andesine to labradorite, and amounts to about 40 per cent of the rock.

Specimen 459 is very similar to 460 and 469 but shows shattering and extreme alteration of feldspar to clinozoisite together with chloritization and epidotization of clinopyroxene along bands corresponding to the septa parallel to 100° which are described under the section dealing with Phase 11 on page 148. Specimen 469 is similar to 460 but contains a thin leucocratic layer of fine granoblastic quartz and feldspar and scattered subhedral to euhedral small brownish green hornblendes. The plagioclase (oligoclase) has slightly higher refractive index than balsam and comprises 40 per cent of the rock; strained quartz 45 per cent and hornblende about 5 per cent.

In the dark layers, parts of the rock have been intensely altered, the feldspar to clinozoisite and the pyroxene to chlorite. The hornblende is darkened and shattered. The alteration is similar to that described for specimen 459.

Ultrabasic gneisses occur in the cores of some of the smaller antiforms and comprise almost pure pyroxene with a little hornblende, olivine and biotite dispersed throughout (fig. XII-39).

Other than to suggest that the lighter bands might well represent metamorphosed, fairly pure, quartzose sandstones and the darker basic layers the metamorphic equivalents of basic lava flows, or sills intruded parallel to the original banding or later foliation, it is not proposed to consider further the ultimate origin of these gneisses.

C. Determination of the Geometry of the Scurrival Fold

Investigation of the geometry of the Scurrival fold was begun by mapping of the regular interfoliation of amphibolitic and quartzo-feldspathic layers as far as possible. Beyond the immediate vicinity of Bagh nan Clach on the west coast of the peninsular where the regular interpoliation of dark and light gneiss is no longer evident, the examination of the structure was continued by using form lines. In areas of exceptionally good exposure like the shore line and on the west flank of

Ben Scurrival, the outcrops of actual foliation surfaces were traced as far as possible and marked directly on the field sheets (map II). The form of the structure within individual well exposed areas was pieced together independently on field sheets. Finally the whole macroscopic structure was built up from the separate field sheets prepared on a scale of 1:2,500 with the aid of statistical plots of information from poorly exposed areas. In the final synthesis, use was made of statistical plots compiled from all the data recorded on the field sheets and comparison made between the geometry of the plots and mesoscopic folds recorded in the field. Wherever possible the attitudes of both planar and linear elements were recorded.

Synthesis of the structure was carried out using combinations of both stratigraphic and statistical methods to see if any significant difference would emerge between the various structural pictures obtained. The difference which could be detected between the results proved to be one of degree rather than one of fundamental importance. Five of the methods employed and their results are listed for purposes of comparison.

(1). The attitudes of foliation measured from each side of the trace of the fold axial surface through Scurrival Point were recorded and the dips and strikes averaged arithmetically to give an average attitude for the north and for the central limb. The dip of the north limb arrived at in this way is 35° towards 340° and for the central limb, 61° towards 58°. These two average limbs when plotted cyclographically intersect in a fold axis plunging at 35° towards 352° (fig. XII-6).

(2). Attitudes of foliation measured in the three areas separated by the outcrop traces of the two fold axial surfaces separating the limbs were plotted separately as S-poles and the maxima obtained were used to define three average limbs. These limbs were plotted cyclographically and the resultant β - diagram gave B plunging at 24° to 338° (figs. XII - 7, 8, 9, 10).

(3). The poles to the foliation measured in all three areas separated by the traces of the axial surfaces (1680 points in all) were plotted and contoured. The pole to the girdle obtained was found to plunge at 25° to 340° (fig. XII-11); a plunge which is again somewhat less than that obtained from the arithmetical averages of the northern portion of the structure.

(4). Plots were made and contoured of attempted measurements of fold axes (fig. XII-12). The fact that the maximum obtained plunges at 25° towards 296° suggests that the maximum is in fact, the resultant of measurements of <u>apparent</u> plunges lying parallel to the Scurrival fold axial trend, Together with axes belonging to folds of F_4. In view of the geometry of the F_2 folds this result was not altogether unexpected and it is thought that if accurate measurement of plunge of minor folds were possible, a strong maximum would be found plunging to the north-north-west.

(5). A β - diagram was prepared from foliation attitudes measured in a small arbitrarily selected area away from the hinge zone of the fold. The area chosen is on the west coast immediately south of Scurrival Point. The plot shows two concentrations. One plunging towards 345° at 15° and one at approximately 25° towards 175°, and these define the F_2 fold axis. The northern maximum is clearly curved about an axis trending south-east in response to 145° (F_3) folding and slight curvature of the southern concentration about a north-east trending axis shows the effect of folding about F_5. An incomplete girdle striking north is the result of regular, shallow folding about F_4 which is responsible for the splitting of the F_2 maximum into a double concentration.

The geometry of this structure makes even an approximation to the true attitude of the fold axis of smaller scale folds difficult to determine as a rule (because of the large angular separation between the trend of fold axes and the measurable strike of the axial surface) and what is usually recorded is the 120° trend of the fold axial surface (figs. XII-2, 13, 25, 26, 29. XIV-35). In fact it was not until the geometry of the Scurrival fold had been ascertained macroscopically that the true axial plunge of the small 120° trending mesoscopic folds was known with certainty, and the true form of even the Scurrival structure itself was not suspected until after mapping was well advanced. It was decided to map the Scurrival peninsular and Ben Scurrival in detail after the exceptionally fine exposure at Bagh nan Clach had been examined in detail and after the discovery on the slopes of Ben Scurrival of some very promising outcrop patterns. As mapping neared completion and most of the attitudes measured in the field had been plotted and analysed statistically, it became possible to verify the fact that the whole peninsular comprised a large scale, overturned fold. At this time too, the relationship became firmly established between the Scurrival structure and zig-zag step folds of Ard Mhor (fig. XII-15) and the folds on Orosay (figs. X-2, 22, 23, 24, 41). The apparent fanning-out of the fold axial trace and the lobate form of the hinges on the map which tends at first sight to suggest a very complex geometrical form can be fairly neatly accounted for by considering the effects of topography on an outcrop surface dipping north, almost parallel to the approximately 25° plunge of the fold axis. The comparative regularity of the structure as clearly shown in the transverse tectonic profile drawn perpendicular to the fold axis looking down plunge (fig. XII-14), contrasts strongly with the form of the structure appearing on the map.

The almost symmetrical form of the Scurrival fold (fig. XII-14) shown by the transverse profile is in agreement with a determination of the axial planar attitude made stereographically on the assumption that the fold is symmetrical. The strike of the axial plane so obtained is 118° (fig. XII-16) and this compares very closely with the 116° strike determined statistically from equal area plots of data related to the axial plane attitude measured in the field (fig. XII-17).

The close similarity in style between the tectonic profile and the profiles of many of the small F_2 folds of the east shore at Scurrival and on Fiary is striking (figs. XII-1, 18). (See also the form of the F_2 fold from Mingulay in figure XII-44). The symmetry of the macroscopic structure within the limits of the traverse profile is orthorhombic (fig. XII-14) since both the axial surface and the plane normal to the fold axis are both planes of symmetry. But considered on a larger scale the overall symmetry is monoclinic (fig. XII-19), a condition which becomes apparent when the angular relationship between the enveloping surface of the fold and the fold axial plane is considered (Turner and Weiss, 1963, p. 123). The overall plane-cylindrical, monoclinic nature of the Scurrival fold would no doubt emerge from consideration of plots of foliation were it not for complicating factors introduced by later folding, particularly of F_5 style, which obscure the symmetry of F_2 structure. But for this, and sampling error introduced by lack of regular exposure, the maximum corresponding to the longer limb would be stronger than for the other (fig. XII-20). In this respect it is unfortunate that the exposure of the north-eastern extension of the northern limb of the fold is lost at the coast to the north and east. The small island of Fiary to the north of Scurrival Point is too far off-shore to provide the exposures necessary to furnish a reliable check on the continuation of the structure because it might easily have been strongly displaced relative to the Scurrival area by major faulting. However, the attitude of the foliation on Fiary suggests that the north limb continues with much the same general strike and is thrown into waves whose crests trend approximately 120°, parallel to the trend of the F_2 fold hinges.

The Scurrival fold as far as determination can be made within the limitations imposed by the nature of the exposure, is thus monoclinic on a macroscopic scale, possessing a penetrative mesoscopic 120° trending, fold axial surface and a north plunging axial direction. It is therefore similar in style to the small scale folds referred to in the F_2 fold. The apparently greater length of the south-south-east striking limbs, an effect arising from the obliquity of axial plunge, disappears in profile (fig. XII-14) and the style is more nearly that of the fold of figure XII-28.

In view of the uncertainty attending measurement of the attitudes of small mesoscopic folds in the little-weathered gneisses, coupled with the triclinicity of the fabric, it was felt that it would be pointless to attempt to determine the existence at Scurrival of fold directions earlier than F_2 which had been folded about the F_2 axis. Nevertheless, the posibility of revealing any such structures by unrolling about F_2 was considered but the results obtained were, as might be expected, inconclusive.

D. Related Mesoscopic F_2 Folds

By reference to the structural profile (fig. XII-14) it is possible to demonstrate the similarity in form between the large Scurrival fold and smaller mesoscopic structures on its flanks such as that shown in figure XII-1. The small fold in the figure is photographed from the south-west so that the direction of view is oblique to the direction of plunge of the structure. Nevertheless the low dips of the north limb, nearest the hammer, and the overturned steeper dipping west limb can be clearly seen. The curve to the west nearest the observer corresponds to the curvature seen in the major structure at the south end of Bagh nan Clach where the foliation reverts from its overturned attitude along the Bagh nan Clach shore and curves around to the west finally running out to sea. In the photograph (fig. XII-1), this, the west limb of the fold, is faulted and is breached by pegmatite so that the continuation of the structure is to some extent obscured.

On a very much smaller scale the same style of folding is viewed almost down plunge in figure XII-21 where a fold of about four inches wavelength in quartzo-feldspathic gneiss, by differential weathering of the more basic adjacent folia, stands out sharply. The axial plunge is almost directly away from the observer and the pencil lies parallel to the trend of the axial plane at 120°. Figures XII-2, 22 show the form of this style of folding in almost horizontal section. Figure XII-2 is taken from a photograph looking along the strike of the axial plane. The photograph of figure XII-22 looks down dip normal to the strike of the overturned limb which here dips east at approximately 65°. The hammer lies on the east striking limb which dips at about 40° to the north. The fold axis can be seen from the white, shadowed band in the left foreground to plunge at approximately 40° towards 352° almost parallel to the hammer head.

Close to the shore on Orosay near the structure shown in figures XII-2, 22, folds of the same style exposed in an E.-W. joint face have been photographed (figs. XII-23, 24); the two views being taken almost at right angles. Figure XII-23 is a view taken in the direction 40° and figure XII-24 in the direction 330°. The attitudes of the steeper overturned south-east striking limb and the flatter east striking limb are clearly shown and the step-fold effect so often seen in E.-W. vertical joint faces is clearly demonstrated (fig. XII-24). The pinched effect in the hinge is due to the fact that the face of the exposure is not planar. It is interesting to note the effects obtained by using different viewpoints, the hammer lies in the same place in each photograph. The dark band at the top left of figure XII-23, trends away from the observer and the appearance of the outcrops is such as to suggest a fold axis plunging away and to the left of the observer approximately in the direction 15°. In figure XII-24 the axis of the structure appears to plunge moderately, directly away from the observer towards 330°. The geometry of this particular type of folding coupled with the marked triclinicity of structure imparted by later folding is largely responsible for the apparent confusion of the structural picture in the gneiss throughout the field.

The curvature of the axial planar trend of this style of folding is further demonstrated on sloping outcrops such as, for example, that in the south side of Ben Eoligarry Mhor behind the schoolhouse (fig. XII-25). (See also figure XIV-35). In this case the photograph is taken in the direction 320° and the dip of the north limb, sloping towards the lower right hand corner of the photograph, is exaggerated by the apparent near horizontality of the exposure which, in fact, slopes moderately steeply toward the lower left hand corner of the photograph. The fracture and shearing at the junction of the sharp overturn between the north and inverted limbs common in this style of folding (figs. XII-1, 21) are shown in this figure.

Smaller scale asymmetrical folding of the same general style can be seen at several localities on the shore below the Thrust at Bruernish and on both the north and south sides of Ard Mhor where it may be very regular in form and sometimes exaggerated by shearing (fig. XII-15). Folding on the south side of Ard Mhor (fig. XII-15) gives the impression of having been greatly steepened by subsequent shear parallel to the general strike of the foliation and the folding is further complicated in this instance by the fact that sheared-out hinges of earlier isoclinal folds add their own distinctive patterns such as that of the almost completely closed fold beside the pencil in the photograph of figure XII-15 which is taken looking towards the south-east. Later anatexis was probably responsible to some extent for the distortion of the folding in the top right hand part of the photograph.

The obscurity of the true attitudes of folds in the absence of strong differential weathering of foliation on glacially smoothed outcrops can be seen at several localities. Even at localities like that on Ben Eoligarry Mor above Eoligarry House (Fig. XII-26) where there has been some weathering, a false impression can be gained of the geometry of the structures. Here the asymmetrical outcrop pattern is not at all clearly displayed except in the middle foreground and trend of the trace of the fold axial surface indicates that those folds belong to the F_2 generation although their appearance, both in the photograph and in the field, often suggests that they are symmetrical plunging folds whose limbs dip with the same degree but in the opposite sense.

E. Genesis of the F_2 Folds

Folding of this phase has every appearance of plastic flexural folding, perhaps brought about by rotation on north plunging axes by a couple with an overturn component directed towards the west (this direction is still recognizable because the gross structure appears to have been little rotated by later orogenies). (fig. XII-27).

Some information concerning the genesis of the Scurrival type of folding can be obtained from consideration of an overturned fold of this style exposed in a joint face south-east of Scurrival peninsular on the south-east shore of Traigh Mhor (fig. XII-28). Here folded, boudinaged basic gneiss forms structures appearing in section as characteristic step folds. The boudinage is clearly earlier than the folding since individual boudins are inclined rather than parallel to the foliation and are jammed together with a tendency for overlap towards the right hand (east) side of the photograph. Other evidence for extension parallel to the foliation prior to the folding, besides boudinage, is to be seen in the presence of quartzo-feldspathic lenses and of folding aligned parallel to foliation. Boudinage folded by this style appears on the east coast of Scurrival peninsular (fig. XII-29). The effects too of lithological differences are demonstrated in this exposure. The basic gneiss has clearly acted in a more rigid fashion in response to folding movements and has produced a simpler form of fold than the surrounding sub-parallel quartzo-feldspathic folia which appear to have responded in a semi-plastic manner so that the folding has been more intense, or exaggerated, to give more complex forms. This is clearly shown above and to the left, and below and to the right of the hinge in the basic band. Notice too that the rigidity of the basic band has produced a step-like fold in cross section and that the vertical limb has acted in the same manner as the spoke of a wheel so that the foliation to the right of the hinge has been bodily "uplifted" and has begun to ride over the other horizontal limb. The plasticity of the surrounding gneiss with its quartzo feldspathic bands has been such as to cause it to respond passively and therefore to some extent in the same fashion to movement but with slightly different style of the basic band. The sharply angular effect resulting from the pivoting action of the basic hinge has been largely absorbed by the more acid layers (fig. XII-30). It is to be expected that local stress immediately to the left of the basic hinge would have been of compression normal to the foliation above the basic band due to the overriding. This stress would have been locally higher than the compression parallel to the foliation hence the lack of smaller asymmetrical folds overthrust from the left (which appear farther to the left), because their formation required minimum compression normal to the foliation. There would have been a corresponding reduction of pressure behind the "knee" of the fold so that the overall shear couple produced strong and exaggerated folding of quartzo-feldspathic layers in this region. Variable intensity of folding in the adjacent quartzo-feldspathic layers appears to hold along the entire length of the basic band shown in the photograph. The difference in thickness of the two limbs of the fold is partly due to later thinning of the horizontal limb, but is largely apparent, because of the attitude of the limbs in relation to the face of the exposure. The attitude of the plane of the profile is responsible also for the absence of overturn in the steep limb.

Plasticity of the gneisses during deformation is indicated by the crumpled form of the folds (fig. XII-26) and, the presence of migmatisation clearly associated with folding in many cases (figs. XII- 1, 23, 24, 25) as well as by the form of the associated minor folds, many of which have a decidedly ptygmatic appearance (figs. XII-31, 32).

Prevalence of vertical (or nearly vertical) foliation striking close to 30° associated with these structures indicates that they must be due to relict attitudes from earlier 30° folding because if overturn producing 120° type folds was from the east-north-east, then 30° vertical foliation might not have been greatly affected by this stress pattern.

Considered macroscopically the structure at Scurrival is a more or less similar, inclined, plunging, plane cylindrical monoclinic fold with corresponding layers maintaining approximately the same thickness on adjacent limbs. Mesoscopically the structure is totally inhomogeneous and a non-plane non-cylindrical fold because of warping of the fold axial surface by late F_5 folding and variation in trend and angle of axial plunge.

The small-folding, seen in places throughout the field to mirror the distinctive asymmetrical style of the macroscopic F_2 fold of Scurrival, appears to be the result of folding during conditions of moderate to considerable plasticity. The evidently plastic style of the small scale folds presents a fairly formidable problem when considered in conjunction with the large scale structure since it is difficult to envisage a fold of these dimensions forming under such plastic conditions. Two possible solutions to this problem seem worthy of consideration.

1). It is possible that at the onset of folding the series of banded gneisses was only slightly plastic due perhaps to depth of burial and incipient anatexis associated with deformation. Under these conditions larger scale folds would be more likely to form than smaller ones because local rigidity would favour transmission of shear. With the progress of deformation accompanying orogeny, rising temperature associated with anatexis would have increased the plasticity of the gneisses, particularly the quartzo-feldspathic layers, so that continually applied stress would be less likely to be transmitted because of local yielding, with the development of small scale asymmetrical folding (fig. XII-33) of the style now recognized as characteristic of F_2 deformation.

2). The second possibility is that the greater portion of the whole mass, with the exception of interfoliated amphibolites resistant to anatexis, was in a semi-plastic state at the onset of folding. These basic layers acted as a rigid framework reinforcing the plastic foliated gneiss which then folded as a unit by hinging of the amphibolites at fractures. Each basic layer then acted as a semi-rigid segmented sheet separated from its neighbour and lubricated by intervening more plastic quartzo-feldspathic layers and tongues of fluid migma. The complete series of interfoliated rigid basic and plastic intermediate and acid gneisses is envisaged as having had sufficient rigidity to fold on a large scale - the stress being transmitted by the rigid frame (fig. XII-34), and on a small scale as drag folds produced by shear due to relative movement of more rigid sections on the eastern flanks after formation of the larger asymmetrical folds (fig. XII-34).

Movement of this type and in this order would serve to explain not only the axial parallelism of associated large and small scale folds but the formation of large-scale folds as well as small, in response to the same applied stress.

F. Other Associated Structures

Although the core of the synform on the west side of the structure is to a large extent drowned beneath Bagh nan Clach there is sufficient exposure in isolated rocks in the bay and on the shore to see that this comprises a series of minor folds some of which produce extremely complex interference patterns (figs. II-1, 2, 3, 4). Generally, however, the larger of the mesoscopic structures are closely similar to one another. This consistent regularity suggests that they have in some measure preserved an orientation bearing a simple relationship to that held when they were first developed and also that they have not therefore been intensively deformed subsequently. These folds appear to be conical in form, tending to be broader and more open at the south-eastern end becoming progressively tighter in the direction of plunge and steep limbed in the north-west (map II). It is possible that they may be the result of folding about late south-south-east axes but they are very similar in style to early isoclinal folds of the type seen at the Croig and are considered to be genetically related to these (Section V, p. 46).

Separation of quartzose bands, parallel to the foliation earlier in the tectonic history of the gneisses has allowed recognition of highly complex interference patterns (fig. II-1) due to subsequent folding. It was found that very closely similar patterns could be reproduced in plasticine by folding a layered aggregate in two directions approximately at right angles and then slicing the resultant structure in an appropriate direction (fig. XII-35).

The layers were first horizontally folded isoclinally and then the axial planes of the isoclines were curved from horizontal to near vertical attitudes about axes parallel to those of the first folds (fig. XII-36). A third set of folds were imposed by bending on steeply plunging axes (fig. XII-37). Vertical slices cut through the structure at different places expose cross sections of varying complexity, including one which is fundamentally the same as the folds pictured from Bagh nan Clach. From the relationships between the artificial fold section and the axes of folding it seems that the Bagh nan Clach section is through a structure originally isoclinally folded so that the strike of the foliation was essentially E.-W. in relation to its present attitude. Later folding bent this structure about north-plunging axes. In view of the general northerly strike of the foliation in this region, an attitude difficult to achieve from an initially E.-W. strike, it seems reasonable to assume that the structures under consideration were formed in the hinge of a fold where the flanks of the early isoclinal folds were closely parallel to the north striking present attitude of the foliation (fig. XII-38).

Little can be said regarding the age of this period of complex folding other than the fact that it might easily be older than the Scurrival phase or in fact the product of dispersion about the later south-south-east axis.

Besides complex structures of the form shown in figure II-1 and the conical folds already mentioned, there are exposed in vertical, approximately east-west striking, joint faces cross sections of isoclinal folds of large amplitude but relatively small wavelength. The presence of these flattened folds indicates that a great proportion of the thickness of gneiss comprising the west flanks of the Scurrival structure is the result of repetition brought about by pre-F_1, tight isoclinal folding, producing structures whose axial planes are sub-parallel to the general attitude of the foliation (fig. V-6).

Figure XII-39 shows the core of a narrow synform and gives some indication of the great increase in complexity in the gneiss of structure in the neighbourhood of the hinges of folds (map II).

Elsewhere the structure appears very much more regular, a feature which becomes evident when attitudes in the crest of the fold comprising Ben Scurrival are contrasted with those of the flanks of the same structure exposed on the north coast of Scurrival peninsula (map II). The apparent complexity in this case is heightened by the effect of a topographic surface lying sub-parallel to the foliation in the crest (fig. XII-40). The cores and hinges of the Bagh nan Clach folds characteristically show pinch and swell structures (fig. XIV-14), shearing and minor crenulations (fig. XII-39). As a rule the darker, basic and more competent gneiss appears to have yielded to deformation by fracture whereas the acid gneisses have responded to differential movement by plastic flow (fig. XII-28).

G. <u>The Overall Structural Effect of the F_2 Folds</u>

Folds of F_2 generation are the governing factor in the overall structure. The imprint on the structural pattern has been locally modified to some extent by large F_4 folds and to a less extent by F_5. It is believed that giant folds of this generation will be seen to control the gross attitude of the foliation, certainly throughout the southern Outer Hebrides, and most probably throughout the whole of the Outer Isles chain. Whether or not F_2 folds are an important structural feature on the Scottish Mainland remains to be seen but the presence there of major axial planar traces trending south-east is regarded as a good indication of their existence.

XIII. THIRD FOLD PERIOD. F_3

Deformation during this period is referred to Phase 10 of the tectonic sequence. The presence of a regular 145° to 155° trending, strongly penetrative lineation exposed on the shore at Halaman Bay, with parallel, symmetrical small scale trough folds, together with folds fluted parallel to their axes at Castlebay suggest a period of folding of comparatively recent age. Some of the effects of this period of deformation can be seen in the alignment of mineral grains, the presence of minute elongate pits where these grains have weathered out, and the presence of fine, narrow grooves, furrows and ribs parallel to other small grooves and folds transecting east striking foliation and folds (fig. XIII-1). The lineation and the folds will be discussed separately.

A. Lineation

In the field the lineation appears at first sight to be the result of the intersection of a subvertical planar structural element which dips at about 80° towards 60° (fig. XIII-3, XV-1). It does not appear to be due to strong dimensional preferred orientation of mineral grains, but rather to slight optical preferred orientation of more or less equant quartz grains which in consequence has produced a differential resistance to weathering and erosion. The feature is not well displayed on freshly exposed surfaces and is in fact best shown where the rock has been subjected to sand blast erosion along the shore. The structure is particularly well developed near the eastern end of Halaman Bay (fig. XIII-2).

The effect when seen on an irregular surface is one of alignment of groups of mineral grains rather than of a series of discrete continuous lines and this can readily be seen in the banded quartzofeldspathic gneiss of figure XIII-3. The nature of expression and coarseness of grain of the structure varies considerably with lithology, pitting parallel to 150° being common in hornblende-bearing gneisses. The impression that the lineation is caused by a subvertical penetrative planar structure is strengthened by examination of non-horizontal surfaces steeply inclined to the direction of the linear trend when it is seen that these surfaces too are lineated (fig.XIII-3).

The regularity of the lineation and its fine structure suggest that it is probably the product of a very late orogeny, because such a comparatively delicate structural feature as this would undoubtedly have been obliterated by later deformation. In many exposures it is oblique to the alignment within the foliation, of elongate minerals like hornblende, a relict fabric from an earlier deformational phase. On the other hand the fact that the linear structure is clearly expressed only in this area suggests that it has in fact been blotted out in other parts of the field by later deformation and anatexis. As can be seen (fig. XIII-3) it crosses folds of both 120° and 100° trending axial surfaces with only slight deviation, and analysis of the relationships of these three structures with the probable complications brought about by a further period of folding about axes plunging to the north-east has proved difficult. Folding on axial surfaces with both 120° and 100°, as well as 60°, trends is only very slight here, so that the effects of interference of one fold by the other, as would be expected, are minimal. Therefore convincing evidence for the order of superposition of different fold periods is unlikely to be found here.

On the shore below the road at Ceann nan Leac (map V) several attitudes of the lineation were measured, mapped and plotted (fig. XIII-4), and while there is clear evidence of variability of plunge and trend on the map as well as in the field this is only slight and does not allow any convincing conclusions to be reached regarding the order of superposition. A plot of attitudes of foliation and accompanying lineation measured from the west end of the beach does however, show that although the change of plunge and trend of the lineation is slight, the orientations are exactly what would be expected if the lineation had been slightly folded about a near horizontal, 100° trending axis (fig. XIII-5). There is reasonably close agreement between this plot and a plot of actual fold axes recorded from the east end of the beach (fig. XIII-6).

It has already been stated that in the field the lineation appears to be the result of a subvertical planar structural feature transecting both foliation and small folds (fig. XIII-2, 3, XV-1). Microscopic petrofabric analysis, however, shows the structure to be a linear feature and it is therefore a true lineation. On the scale of the thin sections examined the rock is a B-tectonite rather than an S-tectonite. Although there is no apparently regular fabric pattern for [0001] axes plotted from the orientation of 760 quartz grains measured from three mutually perpendicular thin sections (fig. XIII-7), no more regular than that of a plot of 560 [0001] quartz axes measured from a specimen collected in the field at random (fig. XIII-8), there is a regular pattern shown by preferred orientation of mica (fig. XIII-9). Plots of poles to {001} cleavage of 550 biotite grains from the same set of oriented thin sections exhibit very slight monoclinic symmetry and disclose a distinct double maximum defining shallow, slightly asymmetrical, sub-horizontal folds whose limbs are of the order of the length of a single mica flake. Alignment of the crests of these folds which plunge at about 5° to 160°, is probably responsible for the sub-vertical planar structure. The fine ribbing and lineation in dominantly quartzo-feldspathic gneiss (fig. XIII-2) is due to minute "rods" formed from aggregations of quartz and feldspar grains around which biotite flakes are oriented.

This structure has been correlated with the 150° trending folds purely on the basis of parallelism of orientation and association in the field.

B. Folds with 150° Axial Trend

All the folds of this generation are mesoscopic in scale and generally comparatively small. They seldom exceed a foot in wavelength and are often very much smaller and in contradistinction to the folds referred to F_2, they are more or less symmetrical and trough shaped in profile with moderately dipping limbs (fig. XIII-1). The axial plunge of these folds is slight and is either to the north-north-west or to the south-south-east. Their distribution appears to be restricted in spite of their being later in age than those of F_2 generation, but they probably occur more frequently than is first apparent because the closeness of trend of their axial surfaces, and similarity of appearance on the ground to folds of the Scurrival F_2 style could lead to confusion.

Just west of the old school at Castlebay a group of small, very shallow cylindrical folds has been exposed in fresh rock by roadworks. These plunge gently to 150° and present a regular fluted appearance due to the presence of fine ribs parallel to their fold axes (fig. XIII-10). Similar folds have been mapped on the shore at Castlebay and folds of this style in thin, $\frac{1}{4}$-inch, quartzo-feldspathic veins are exposed in scarps on the hill above the Secondary School. On the hillside south of Loch Micleod there are small folds trending 150° and in some exposures hornblende crystals approximately 2 millimetres in length are aligned in the same direction.

The restriction in distribution of structures of this generation, and in particular that of the lineation, is readily accounted for by virtue of their likely susceptibility to obliteration by later deformation. In this respect their distribution in relation to later folding at Halaman Bay can be seen to be fairly consistent. Wherever the lineation is intensely imprinted, as at the east end of the bay, F_4 100° trending folds are of only slight intensity, forming, as a rule, very shallow troughs (fig. XIII-3), whereas at the west end of the bay strong folds around 100° trending axes are not obviously crossed by the lineation. To some extent this effect is illustrated by photographs taken in these areas. Figure XIII-1 shows a small 150° trending fold near the west end of the beach close to a large 100° trending fold with which there is no marked associated lineation. The lineation in the photograph is clearly very much fainter than that displayed in photographs from the less strongly F_4 folded east end of the beach (figs. XIII-2, 3). Elsewhere in the field, folds of F_4 generation tend to be very much more strongly expressed (figs. XIV-6, 10) thereby accounting for the absence of the 150° trending lineation.[4]

No instances have been seen of migmatites and quartzo-feldspathic veins associated with 100° F_4 folding intersected by lineation trending 150°. This further reinforces the evidence for the relative ages of the two fold periods since later migmatisation associated particularly with strong 100° trending folds having steep and sheared axial surfaces has completely obliterated the finer lineation imprinted prior to F_4. The absence of 150° lineations in gneiss locally strongly affected by 100° folding can be seen also in photographs of exposures near the west end of Halaman Beach only a few yards from lineated gneiss (Compare the photographs of figures XIII-2 and XIV-2

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4. At Mingulay similar 150° trending lineation appears only on rocks exposed on the beach. It is clear then that sandblast erosion is necessary before this structural feature becomes obvious. (See Addendum p. 141).

taken about 50 yards apart on Halaman Beach)[4].

Cross cutting relationships with folds of 100° and 60° trends (fig. XIII-3) (map V) show reasonably convincingly that folds and lineation trending 150° are earlier. In addition, 160° trending quartzo-feldspathic pegmatite veins at Leenish which are believed to be related to F_3 folds are corrugated by F_4 style folds. The chronological relationship of these folds to folds of the Scurrival F_2 style cannot however, be demonstrated so easily because it might be argued that their absence in other localities could just as well be attributed to obliteration by F_2 folds as to the effects of the 100° or 60° trending folds.

Against the preceding evidence there is on the west coast, faint lineation possibly of F_3 generation, crossing later folds south of Bagh nan Clach near Eoligarry (fig. XIV-1) and F_3 folds are exposed at Vaslain (fig. XII-11). However, because it is believed that the large scale reorientation of the foliation is the result of folding of the Scurrival generation and because the broad outcrop pattern of the gneisses in the vicinity of Halaman Bay is of the style associated with F_2 Scurrival type folding, it is concluded that the 150° trending folds and lineation are later than F_2 because they transect the foliation regardless of its orientation. This is so, even though the strike of the foliation varies from 0° to 90° at Halaman Bay, whereas both folds and lineation exhibit no more dispersion than is shown in the plots of figures XIII-4, 5 and 6.

C. Genesis of 150° Trending Structures

Thin section petrofabric analysis of the lineation shows this to be due to almost horizontal submicroscopic fold axes and field mapping of 150° trending folds shows that these also plunge only very gently to the north-west or south-east. The equal area plot of the attitudes of biotite flakes reveals a very faint suggestion of asymmetry in the style of the microscopic folds which is not apparent in the mesoscopic folds and this suggests that the F_3 structures owe their formation to compression with slight rotation indicating a slight tendency towards overthrust from the south-west. These movements affected the gneiss when it was at a depth great enough for it to respond to deformation in a plastic manner. The regularity of the lineation and the folds, both in form and trend suggests that the degree of plasticity attained was only slight. The forces involved may have been related to those responsible for the formation of the F_2 folds and from a similar direction, but of considerably less intensity. Further consideration of the nature of these forces would be so highly speculative that any conclusions reached would be of debatable value.

Addendum:

Following the discovery on sandblasted gneisses at Mingulay of lineation similar to that exposed at Halaman Bay, a search was made for other exposures of this structure along the west coast of Barra. It was found that lineation can be seen in certain lights on rocks exposed between sand dunes at Cuier and Allasdale, and three distinct trends were recognized. At Sgeir Liath south-east trending lineation transects pseudotachylite and thrust breccia, and in most exposures the lineation can be seen to cross-cut structures as late as F_4. Measurements of trend at Allasdale show a regular swing of one set of lineations from 0° to 35° and this is considered to be due to folding about F_5. The subvertical planar nature of the structure is considered to be the expression of extremely fine jointing and a plot of trends of the structure show concentrations grouped in approximately the same positions as those obtained for the plot of joints measured from aerial photographs (fig. XVIII-73). It is concluded therefore that the suggested relationship between the large scale joints and the dominant F_4 fold pattern (p. 199) is correct. The fact that some linear trends appear to be more strongly developed in some exposures is due in part to the direction of the incident light, but depends largely on the local direction of the prevailing wind. Where the wind tends to blow more nearly parallel to one linear direction this becomes accentuated, often to the exclusion of the other trends.

It seems therefore that the fine fractures visible in thin section resulting from the lineation seen in the field are not related to the B-lineation determined from petrofabric analysis of the attitudes of biotite flakes. The parallelism of this F_3, B-lineation and the south-east trending micro-jointing is purely fortuitous. Furthermore this brings the corroborative evidence for the lower age limit of the thrusting to immediately prior to F_4 deformation. (See footnote 8, p.

150), although other field evidence suggests that the thrusting began earlier in the tectonic history of the gneiss.

XIV. FOURTH FOLD PERIOD. F_4

A. Folds with 100° Axial Trend

Almost everywhere in the field there are folds with a consistent 100° axial planar trend which are horizontal or plunge at moderate angles to the east or west (fig. XIV-1). The deformation responsible for the genesis of these folds is referred to the eleventh phase of the tectonic chronology outlined on page 41. The 100° trend varies but little, either within any one locality or from place to place in the island, although in some exposures fold systems with subparallel trends can be seen to merge (figs. XIV-1, 2, 3). A notable exception to this general condition is in the area exposed at Halaman Bay near Tangusdale where the trend of folds can be seen to swing between 80° to 130° in response to later cross folding which produces curvature of axial planar trend[5] similar to that displayed by F_2 folds at the same locality (fig. XII-4).

The style of these folds varies throughout the field, depending on their position on the major structure (fig. XIV-4). Where the foliation strikes perpendicular to their trend they tend to be symmetrical in cross section and of open, moderately shallow form (figs. XIV-1, 5) ranging from a few inches to a foot in wavelength. Although they are generally of this comparatively short wavelength much larger folds do occur with wavelengths of up to ten or twenty feet. In profile they vary from shallow U-shape (fig. XIV-1) to V-

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[5] Similar curvature is very well displayed at Guarsay Mor, Mingulay (fig. XIV-34) and at Hecla Point, Mingulay there is a striking example of an F_2 fold axial surface curved by F_4 folding (fig. XIV-35).

shape (fig. XIV-5, 6) and even chevron style. When developed in this form they display orthorhombic symmetry. In other localities where the axial planar trend is oblique to the strike of the foliation they commonly display an asymmetrical habit and are then symmetrilogically monoclinic, particularly when folding has been associated with axial planar shear (fig. XIV-7).

Where the foliation dips to the north-west or north-east the north facing limbs are steeper than those dipping south (fig. XIV-7), and in localities where the foliation dips in the opposite sense the converse holds true for the dip on the limbs of the small folds (fig. XIV-8). The general style of the asymmetrical folding is one of isolated folds separated by stretches of unfolded banding equal in length to several times the fold wavelength (figs. XIV-2, 9). As the symmetry increases the separation between adjacent fold axial planes becomes more nearly equal (fig. XIV-1). Axial planar shearing associated with migmatisation and injection of quartzo-feldspathic pegmatite veins is usually, but not always, confined to folds showing marked asymmetry (figs. XIV-7, 9).

The expression of F_4 folds varies with the local average attitude of the foliation in another way. Where the foliation is steeply inclined and nearly perpendicular to the fold axial surface, the intensity of folding reaches a maximum (figs. XIV-5, 6, 10) and it is least in areas where the foliation lies almost parallel to the fold axial trend. The intensity of folding seems to have been reduced to some extent whenever the foliation includes thick basic bands. This further suggests that folding took place under conditions of incipient anatexis when the quartzo-feldspathic portion of the foliation was semiplastic but while the interfoliated basic members were still substantially rigid. This effect is clearly seen at two localities where the attitude of the foliation is essentially the same; on the west coast of Scurrival and at Bagh nan Clach. In the first instance thick basic bands have prevented strong folding (fig. IX-5) whereas at the second locality folding has been moderately strong (figs. XIV-5, 6). The other factor affecting the aspect of the folds in the field, the attitude of the surface of the exposure (fig. XIV-11), can be seen in several places throughout the field.

As might be expected, folding has been most regular in gneisses comprising fairly regular alternating quartzo-feldspathic and darker gneisses. To some extent the latter layers appear to have exerted a control over the style of folding and prevented disharmonic and conjugate folding similar to the ptymatic style (not necessarily related to F_4) exposed in quartzo-feldspathic gneiss of intermediate composition at Bagh nan Clach (fig. XIV-12).

The axial surfaces of this fold generation are without exception vertical or steeply dipping to the south and measured attitudes of some examples are listed in Table 7. The axial plunge depends on the initial attitude of the foliation and in much of the field is slight to moderate.

Table 7. Attitudes of structural features related to F_4 axial surfaces

Locality	Aerial Photo No.	Strike	Dip Angle	Dip direction	Nature
Doirlinn	2169	100°	80°	South	Fold axial planes
Doirlinn	2169	100°			Fold axial planes
Bagh nan Clach	1163	100°			Septa
Bagh nan Clach	1163	125°	90°		Septa
Fiary	1165	110°	90°		Septa
Fiary	1165	125°			Fold axial planes
Halaman Bay	4156	100°	80°	South	Fold axial planes
Halaman Bay	4156	110°	80°	South	Fold axial planes
Halaman Bay	4156	95°	80°	South	Fold axial planes
Ceann nan Leac	4158	100°	90°		Fold axial planes
Eoligarry	4458	85°	90°		Septa
Eoligarry	4458	80°	90°		Septa

An example of gently plunging, east trending folds which are not related to clearly defined subvertical axial surfaces occurs on the west coast of Fiary (fig. XIV-13). Here the folding is disharmonic but individual sets of folds nevertheless retain the steeply inclined style of axial surface. The style of the whole system of folds is similar to that of conjugate folding (Johnston, 1956) or simple polyclinal folding (Greenly, 1919) but in the present instance the individual axial surfaces are parallel[6]. Similar effects are seen elsewhere where disharmony is so

[6] An example of conjugate style of folding has been seen on the island of Mingulay at Guarsay Mor where the axes of folds of two generations, F_2 and F_4 converge (fig. XIV-33).

pronounced as to produce pinch and swell structures (fig. XIV-14).

B. Fold Genesis

Movement associated with the folding appears to have been almost perpendicular to the fold axial surfaces and this has produced simple flexural folds (figs. XIV-5, 6) in most cases. On the flanks of large structures where the foliation lies oblique to the 100° fold axial trend, the asymmetry of style of this generation of folding became exaggerated to such an extent that shearing parallel to one set of limbs occurred with concomittant injection, and probable formation *in situ* of quartzo-feldspathic fluid. As the gneiss was in a state of incipient anatexis at this time it is possible that shear would have been sufficient to destroy the last semblance of rigidity along the axial surfaces of folds in material which by that time was in all probability little more rigid than a highly viscous paste.

In some styles of folding parallel to this direction the folia appear to be dragged in the same sense on either side of the axial surface and this suggests that movement of material, in either the solid state or as a fluid, has caused the development of a special type of drag fold, or that the crests of the folds have ruptured under pressure of accumulated quartzo-feldspathic fluid which has migrated perpendicular to the direction of maximum stress and parallel to the fold axial surface. The mechanism of formation of this type of "drag folding" may have been similar to, and would therefore agree with, that which produced the flexure folding (fig. XIV-15). In some cases there is a suggestion that migma moved from quartzo-feldspathic bands into axial planes and tension fractures in response to pressure directed perpendicular to the foliation and this resulted in thinning of the bands nearest the axial planar tension fractures (fig. XIV-32).

With repeated compression and some associated shear and migmatization along preferential planes (in this case the axial planes) normal to the direction of compression, quartzo-feldspathic material derived locally and from anatectic sites nearby would, under these conditions, have been forced along the axial surfaces to areas of slightly lower pressure (fig. XIV-16) thus causing down-dragging and fracture. Wherever boudinage had taken place earlier, this process could lead finally to drag on the end of boudins (fig. XIV-17) in situations where these were suitably oriented.

An alternative consideration is that this type of folding was developed only in the immediate proximity of already formed boudins (figs. XIV-18, IX-4, 5, 6). But many of the structures of this type were probably formed when P_{max} was directed in a plane parallel to the fold axial direction (i.e. 100^{o}) during boudinage (Ramberg, 1956, p. 516) and upon separation of the boudins, flow took place into the fractures which were formed (figs. XIV-19, 20, IX-5). Folds of the type shown in figure XIV-9 appear to have formed in this way in response to a mechanism completely incompatible with that required to form folds of flexural type whose development implies compression at right angles to that necessary for boudinage (fig. XIV-21). There is little doubt that these folds associated only with boudinage which appear to belong to an earlier generation (associated with the development of boudins) are in fact generated at the close of compressional deformation responsible for flexural folding when locally formed migma seeped from the foliation into axial planar tension fractures. Combinations of both types of fold are not uncommon and are exposed in the cliffs south of Doirlinn (fig. IX-4).

Boudinage in which the separation trends east, presumably formed when compression was directed perpendicular to the foliation and in a direction relative to the foliation which now corresponds to a trend of approximately 100°. This compression may have produced similar drag-type folds which were later amplified and modified by approximately north-directed compression responsible for the generation of the 100° trending folds of F_4 (fig. XIV-22).

C. Septa Parallel to 100°

A sequence of events similar to that just proposed for the genesis of the folds formed during the phase of deformation under discussion might account for the fact that the distinctive lineation paralleling this fold direction is markedly different from any hitherto recognized structure[7] associated with the periods of deformation described

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[7] The well exposed sandblasted outcrops at Mingulay Bay show that lineation due to planar structural features is fairly commonly developed, although rarely seen, in the gneisses. Thin sections of finely lineated gneisses from Mingulay show them to be transected by finely sub-parallel dusty lines cutting across individual mineral grains. (See Addendum p. 141).

so far (fig. XIV-23); That is, different from the microfolding and rodding association with the earlier 150° direction of folding and the dimensional and optical alignment of mineral grains associated with isoclinal folding and shearing of even early orogenies.

In this case the lineation is the product of the intersection with the foliation or the surface of the exposure of a series of discrete, coarse, subvertical planar structures and is penetrative only on a mesoscopic and macroscopic scale. Its surface expression varies considerably and ranges from ribs up to 2 inches wide which may sometimes stand as much as 3 inches or more above the outcrop surface (fig. XIV-24) to fine ribs of the order of a millimetre wide with a surface relief of a comparable order of magnitude. The spacing between the septa ranges, on the average, between 1 to 4 times the width (figs. XIV-25, 29) but varies considerably.

Although attitudes varying between approximately 100° and 120° have been measured in the field, it is usual to find septa of differing strikes occurring together rather than in groups of the same trend as can be seen for example on the north side of Ben Eoligerry Mhor (fig. XIV-26). In this respect their trends agree closely with those of the fold axial trends at Halaman Bay and elsewhere (fig. XIV-2). The possibility that these structures may represent conjugate sets of shears (fig. XIV-27) related to the earliest stages of thrusting (cf. figs. XVIII-48, 51), in spite perhaps of their fitting postulated stress fields, can reasonably be ruled out on the basis of their very restricted distribution and because of their trend. The narrowness of this distribution within different rock types implies that they have been considerably affected by later deformation which has obliterated them in most areas. This is unlikely to have happened if they were genetically related to so late a structural feature as the Hebridean Thrusting.[8] In the field the different mineralogical character is not apparent in those septa cutting quartzo-feldspathic acid to intermediate gneisses but those transecting dark amphibolites always weather to a rusty brown colour. The age of these planar structures is readily demonstrated since, apart from the fact that they are only occasionally seen to bend markedly (fig. XIV-23), they can be seen cutting several comparatively later structures like the agmatite of south-east Bruernish in which the original foliation of the breccia although individual fragments are randomly oriented from piece to piece (fig. XIX-13) is still recognizable. A further but less well defined example of ribs transecting all visible structural features can be seen on the shore near Orosay, Traigh Mhor (fig. XIV-28).

Thin section examination of hand specimens of the septa from Bagh nan Clach and lineated agmatites from Bruernish shows the linear structure of this generation to be markedly different in character from that seen at Halaman Bay. That part of the rock comprising the ribs contains shattered mineral grains and is cut by fine hairline fractures

[8] The presence on the east coast of Mingulay of pseudotachylite lineated parallel to 120° and 150° provides confirmation of the fact that thrusting began early in the tectonic history of the gneisses. (See Addendum p. 141).

parallel to the septa and to larger fractures which are seen in the field to split the septa through the middle (fig. XIV-29). The plagioclase has been almost completely replaced by clinozoisite and the pyroxene has been epidotized. The edges of the septa are quite clearly defined, even in thin section and can be seen cutting across individual mineral grains (fig. XIV-30). The structures are clearly the result of low grade, cataclastic metamorphism. The retrogressive metamorphic replacement of feldspar by clinozoisite explains why despite the shattered nature of their constituent minerals, the septa are more resistant to weathering and erosion compared with the adjacent gneisses in which the feldspars are more susceptible to atmospheric weathering effects.

The distribution of the ribs and septa is restricted (in as far as exposure will allow determination of this) to the immediate vicinity of Bagh nan Clach at Scurrival and Eoligarry. Finer lineation only has been seen at one other locality a few hundred yards north-west of Bruernish Point where it transects agmatite. In its limited distribution it shares a common feature with the 150° lineation at Tangusdale. This irregular distribution, coupled with the fact that in each case the structure is well developed suggests either that both structures formed under rather special conditions or that they have been obliterated by later deformation elsewhere in the field. Had their distribution been simply due to obliteration except in the areas described, then one could reasonably expect to find 100° trending septa at Tangusdale as well as the 150° lineation and, although less likely, 150° lineation could be expected at Scurrival. Against this it may be noted that deformation sufficiently intense to produce septation is likely to obliterate earlier lineation like that at Halaman Bay.

The structures are clearly not confined to any particular lithology or group of lithologies, being present in gneisses ranging from light, buff-coloured, acid to almost black, basic composition (fig. XIV-25). In some places they appear to have been affected by later pegmatites (fig. XIV-29) and in others they are clearly obliterated by later mobilization (fig. XIV-24). But on the other hand lineation in places obviously cuts across pegmatite veins associated with agmatite (fig. XIX-13). Elsewhere at Bagh nan Clach shear parallel to foliation has offset these septa and has even resulted in change of their orientation, producing curvature (fig. XIV-23). The foregoing factors point to a time of origin for the lineation which is later than that for agmatite and associated pegmatite (fig. XIX-13) and earlier than some mobilization and foliation shear, and it may therefore be as early as the F_2 Scurrival folding because a few ribs trend at 120°. On this basis the stress pattern responsible for their genesis might agree with a stress field similar to that producing the overturned fold system with the 120° trending axial. If this were the case one might reasonably expect to find the lineation at Bruernish and ribbing at Bagh nan Clach to have been affected by 150° folds but no evidence of this has been seen. Furthermore at Bagh nan Clach very faint 100° trending lineation stands oblique to 120° trending fold axial planes (fig. XIV-31) and is thus clearly later than F_2. If one accepts that the septation is related to F_4 then it is conceivable that it represents tension fractures developed parallel to the fold axial trend at the close of orogeny with relief of stress in a manner similar to that proposed for the emplacement of quartzo-feldspathic pegmatite veins parallel to fold axial trends. The tension fractures thus developed would provide paths for the solutions that have brought about the metamorphic changes in the mineralogy within the ribs by growth of clinozoisite and clouding of feldspars (fig. XIV-30). The grade of this metamorphism is considerably lower than that generally evidenced by the gneisses. In this respect, but for their orientation, and in view of the brittle nature of the deformation responsible for its genesis and the commonly occurring intersecting arrangement of the structures, the impression could be given of sets of conjugate shear surfaces (fig. XIV-27) perhaps related to the earlier stages of movement on the Hebridean Thrust (figs. XVIII-48, 51).

Since the ribs have clearly been subjected to the effects of later anatexis it must be assumed that only in the Bagh nan Clach area has the gneiss escaped conditions of widespread anatexis later than the time of the F_4 fold generation. Conversely it seems more reasonable to suppose that septa formed only in those areas which were subjected to anatectic effects of a particular intensity at certain crustal levels where the necessary metamorphosing fluids were available, as a final or very late stage effect following the development of fractures parallel to axial surfaces. This hypothesis would tie in well with the observed fact that no 150° trending lineation is associated with the Bagh nan Clach 100° trending lineation (because it was obliterated by this postulated late stage anatexis) and would also account for the absence of the 100° trending lineation in rocks clearly preserving earlier and finer linear features at Halaman Bay but also affected by 100° trending folds.[9] Some 100° trending folds as at Halaman Bay could still have been (as appears to be the case in the field) associated with migmatite in the immediate vicinity of their axial surfaces at higher levels where migma was intrusive rather than diffusive.

Addendum.

Fine lineation trending north-north-east, south-south-east and east recorded from gneiss exposed at the shore near Allasdale suggests that very fine jointing related to F_4 deformation is still detectable. (See p. 141).

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9 In view of what has been observed in lineated sandblasted gneisses at Mingulay, the absence of the 150° trending lineation at Bagh nan Clach might be accounted for by the lack of sandblasting of the rocks but this argument could not be applied at Halaman Bay where the gneisses have been subjected to intense sandblasting and do not display 100° lineation. (See Addendum, p. 141).

XV. FIFTH FOLD PERIOD. F_5

The latest fold phase recognized in the field is that which has caused clearly discernible curvature of the limbs and axes of the products of most of the earlier fold phases including the ubiquitous 100° trending F_4 fold direction. Structures of this generation are referred to the twelfth phase of tectonic activity.

Folds which plunge moderately (compared with the plunge of many structures) at between 10° and 40° to the north-east (or in places south-west) can be seen at the coast near, and north of Tangusdale, Halaman Bay and at a number of other localities in the Scurrival area. In style these range from very broad open folds with wavelength several times their amplitude to rare moderate folds with a wavelength equal to about twice their amplitude (figs. XV-1, 2, 5).

In exposures at Halaman Bay folds of F_4 style, with trends averaging approximately 100° can be traced around the limbs of north-east plunging folds of F_5 generation and their change in trend from about 90° to approximately 120° is clearly visible. Similar curvature of F_2 folds from 120° to 150° can be seen in horizontal section on the shore at the west end of the bay. (fig. XII-4). Below the road north of Tangusdale on the rocks of the shore at Ceann nan Leac, folds and lineation of the earlier 150° trend can be seen swinging slightly as they cross an elongated dome of amphibolite and quartzo-feldspathic gneiss whose long axis trends approximately east-north-east (map V). Curvature of asymmetrical folds typical of the F_2 style on the west coast of Scurrival and of the limbs of the major Scurrival structure are also considered to be due to warping about this later north-east fold axis. In some places reversal of plunge of smaller scale, microscopic F_2 type folds can be ascribed to warping about late north-easterly plunging fold axes as well as to folding about F_4 (fig. XII-42). It is possible too that the curvature of the Bagh nan Clach 100° septa already noted as probably due to shear parallel to the foliation is due to the effects of this period of folding since the curvature in this case is in the same sense as that of the limbs of the 120° structure (figs. XIV-23, map II). Curvature of 100° type septa is not generally recognized, however, and this is to be expected in view of the comparatively shallow plunges of the north-east axes and the almost vertical attitudes of the septa which are aligned at a high angle to the fold axis (fig. XV-3). The attitudes of foliation defining a broad fold on the west flank of Beinn Mhartuin plotted as a β-diagram define an axis plunging at 40° towards 50° (fig. XVIII-25). The elongated dome shaped fold with its attendant complex folding on the shore south of Brevig Bay (fig. XV-4) is probably another example of this later north-east type of structure.

One other feature associated with this latest phase of folding has been noted on one occasion near the south-east coast. Here on an exposure parallel to the ac plane of a small north-east plunging fold, there is a lineation which lies parallel to the axial plane of the structure (fig. XV-5). In appearance this is remarkably similar to the faint lineation paralleling the 100° fold direction, being exposed as a series of fine ribs, and in all probability it owes its origin to a similar mechanism. The parallelism of the lineation with the axial plane of the fold and its concentration in this case in the hinge region suggests that its position was controlled by axial plane cleavage which has since healed, but if this were so the structure would be unlikely to survive except from a very late fold phase and structures of this style are thus distinguished from north-north-east plunging folds of the earliest 30° plunging F_1 style.[10] Very early north-north-east F_1 folds plunge to the north-east also but any suggestion that the two may be related chronologically must be considered along with the fact that north-east plunging folds of a broad open style at Halaman Bay have 100° trending F_4 folds curving around their flanks. In this case it appears reasonable to say that the 30° steep or vertical strikes associated with folding which have been seen in a number of instances especially in Orosay, Traigh Mhor and in the north of Barra generally are distinct from the north-east latest recognized folds because the latter sometimes preserve axial planar features and are typically open in style and generally manifestly more in the character of broad warping.

[10] Lineation parallel to the early north-north-east folds has been found at Mingulay Bay and is seen to be due to alignment of aggregates of the constituent minerals in rods about 3 millimetres in diameter. This is quite distinct in character from the late north-east fold axial planar feature described from Barra. (See Addendum p. 141).

Warping of this generation may have been in response to moderate compressive forces similar in nature to those responsible for the later thrusting, but the gneisses on which these forces acted to produce F_5 folds were plastic rather than brittle.

XVI. THRUSTING

A. General Description of the Thrust

Clear evidence for thrusting at more than one period in the history of the gneisses lies in the presence of contorted pseudotachylite veins in some places in the field.[11] The age of the main Hebridean Thrusting, however, postdates the later north-east fold phase and is prior to the intrusion of any of the post Cambrian dykes seen to cross the line of the main Thrust surface. The thrusting is referred to Phase 13 of the tectonic history. Two principal zones of thrusting associated with thick soles of pseudotachylite outcrop on the island on the west flanks of Ben Tangaval and Heaval.

The boundary of the eastern overthrust mass is by far the most prominent. It runs from the east coast of the island of Vatersay in the south, through Castlebay where it forms a prominent feature on the hill (fig. XVI-1), almost due north to the west of Heaval and Hartaval, between Grianan and Beinn Mhartuin, and curving east under the north shoulder of Ben Verrisey continues south along the flank of Ben Obe to Loch Obe (fig. XVI-2). It then trends slightly north of east behind Bruernish village south-west of the summit of Bruernish out to sea at Rudha Micheil north-east towards the small island of Fuiay. The width of the zone of thrusting and exposure of the thrust plane varies considerably in extent depending in part on the topography but

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[11] Lineation parallel to 150° cutting pseudotachylite at Mingulay Bay on the southern island of Mingulay confirms this early age. (See Addendum p. 141).

largely on the attitude of the thrust which itself shows considerable variability. The width of the thrust sole exposed is least at Castlebay and to the west of Heaval where it is approximately 200 yards and greatest in the Cuier area where it attains a width of more than a mile. In the vicinity of Castlebay the dip of the thrust surface is in the region of 35° eastwards whereas at Cuier the surface rolls over to dip in a westerly direction down to, and presumably below, sea level north of Sgeir Liath where pseudotachylite breccia forms isolated rocks between high and low water marks on the beach. The segment of overthrust gneiss comprising the eastern part of the island appears to form a lobe projecting westwards from the line of the main Hebridean thrust belt.

A less well defined parallel thrust through the gneiss occurs at the south shore west of Castlebay and across the west flank of Ben Tangaval striking approximately north, with trends swinging from north-west at the Sound of Vatersay in the south to north-east at Ard na Gregaid in the north.

The attitudes of the thrust surfaces are clearly controlled by that of the foliation whose dip varies from about 50° just north of Castlebay to horizontal or slightly west-dipping at the shore near Allasdale. Many instances can be seen where the attitude of the thrust surface alters to follow the changed attitude of the foliation over a fold and for a greater part of its length immediately north of Castlebay north-trending folds lie along the outcrop of the thrust.

These folds are considered to be the cause of the thrust's location rather than its effect since they agree in style and orientation with folds elsewhere and do not appear to cut across any recognizably earlier trends. In this respect the structural relationship between thrusting and folding differs from that described by Kursten (1957, p.14) of Choinnich, South Uist.

Parallelism of these thrust zones which form part of the Hebridean Thrust, with that of the Moine suggest that the two may be structurally as well as temporally related as suggested by McIntyre (1954).

Conclusive evidence for the direction of movement of the overthrust mass has been found at only one locality. However, had the scope of the overall investigation been less wide so that more time could have been devoted to this particular aspect, it is not unlikely that further evidence would have been found, provided exposure is adequate. On the hillside above Castlebay north of the Glen an east-trending joint forms a striking feature which can be followed as a small scarp and trench across the terrain. North of the Glen there is a conspicuous crag of light coloured gneiss (fig. XVI-3) immediately to the east and above the outcrop of the thrust surface (fig. XVI-4) and on a south-facing joint surface of this crag are to be seen the intersections of numerous well developed sigmoidal tension gashes (fig. XVI-5). The joint face which is vertical strikes approximately east and the tension gashes can be seen to be striking approximately south.

Tracings of these sigmoidal tension gashes and measurement of the most inclined of these, and therefore the least rotated, give an average orientation of 40° towards the west. The attitude of the thrust force has been determined on the basis of the results of experimental work by Riedel (1929) in which he has shown that in brittle materials undergoing shear, tension gashes form in the shear zone inclined at 45° to the line of shear, that is to the directions of the couple producing this shear (fig. XVI-6). Further shearing results in lengthening of the tension gashes at 45° to the line of shearing but rotation of the central portion of the fractures produces a sigmoidal form. Shear fractures oblique to the direction of the shear couple (fig. XVI-6) are probably represented by the sub horizontal fractures dipping gently to the west in the photograph of figure XVI-5.

This attitude of the sigmoidal tension gashes inclined at 40° west suggests on the basis of Riedel's (1929) work that the orientation of the thrust force and therefore the movement is to the west in a surface whose average dip is approximately 5° to the east (fig. XVI-7). It is probable that this dip should be slightly higher because the latest formed and therefore un-rotated ends on the gashes may well be too fine to show with sufficient clarity for measurement. This attitude is confirmed by measurement of an average dip of the thrust surface based on the greatest height above sea level just west of Heaval approximately 1 mile distant perpendicular to the strike from the line at which the sole reaches sea level (fig. XVI-8). The difference in elevation is approximately 575 feet and the average dip to the east when calculated is therefore about $6\frac{1}{2}^{o}$. The slope of the east flank of Beinn Mhartuin (fig. XVI-9) is more or less coincident with the sole of the thrust and here there is a difference of elevation of about 375 feet between the saddle at 425 feet and the summit of Beinn Mhartuin over a distance of half a mile to give a dip of about $8\frac{1}{2}^{o}$. Both these figures for the angle of dip are of the same order as that determined from the attitude of the sigmoidal tension gashes.

Locally the dip of the thrust surface can be seen to vary considerably as at Castlebay where the dip of 35^{o} to the east is very close to that of the foliation at this locality (fig. XVI-1). Near Cuier the direction of dip is seen to flatten and change to the west to reach sea level on the shore north of Sgeir Liath (map I).

It is thought that the thrusting from the east is responsible for the strong east striking subvertical joint patterns displayed in the gneisses (figs. XVII-3, XVIII-40) which shows very clearly on aerial photographs of the region (fig. XVI-14). Aerial photographs also suggest that some at least of the jointing is not post-thrusting and normally only those joints parallel to direction of thrusting tend to continue, although with different degrees of expression in many cases, across the outcrops of the thrust surface. On the whole, however, examination of aerial photographs gives the impression that much of the jointing expressed in the gneisses at present is either contemporaneous with, or later than, the thrusting.

In order to investigate this question further aerial photographs covering the country bounding the thrust outcrop were trimmed and assembled so as to give complete coverage of the whole area. From this "mosaic" it was possible to follow the trace of joints across the line of the thrust and it soon became evident that there is no clear evidence for displacement of joints by later thrusting. Doubtful cases of joints fading out at the thrust contact could reasonably be put down to the effects of the slight changes of lithology encountered across the thrust surface with result variation in expression of joint fractures.

It is considered nevertheless that although this relationship between large scale joints implies that the thrusting was not later than the jointing and may indeed have been earlier, it is possible that much of the smaller scale jointing in the gneisses is the result of deformation earlier than that accompanied by thrusting, such as F_5 folding. On the other hand, the continuity of joints and later dykes across the Thrust indicates that thrusting was not the final event in the tectonic history of the gneiss.

From the general trend of foliation when compared with that above and below the thrusts from aerial photographs, surface outcrops suggest that clockwise rotation has accompanied the thrusting. That rotation has in fact taken place is confirmed by equal area plots of the attitudes of fold axes measured from above and below the surface of the Heaval Thrust (figs. XVIII-10, 11). The maximum obtained from a plot of 180 fold axes measured on the overthrust block shows a clockwise rotation of trend from 100° to 120° as compared with the trend below the Thrust. In addition the plot of 920 axes below the Thrust shows steepening of the angle of plunge from 10° to 40° which indicates that a certain amount of tilting has taken place also. Had a greater area of overthrust gneiss on the island survived erosion - particularly in the west where the attitude of the thrusting is flat, and in some cases towards the west - it is possible that any impression of overall tilt towards the east would be cancelled out or much reduced by measurements taken where gravity sliding and tilt to the west will have affected the gneisses. Plots of poles to foliation similarly indicate that rotation has had a strong effect on the attitude of structures subsequent to thrusting. This evidence has led to the following conclusion regarding structural comparison with other districts; without knowing the extent to which thrusting has affected the gneisses of the area under investigation or the degree of rotation and tilting involved, it could be very difficult, and indeed unwise, to attempt correlation on the basis of single fold axial trends, with fold periods recognisable in the Scottish Mainland. This reservation would probably also hold for correlation with other parts of the Outer Hebrides except that a regular variation of trend throughout the length of the island chain is likely to be encountered.

If the sense of rotation of the overthrust block is constant along the length of the thrust belt of the Outer Isles then it would be reasonable to postulate an associated dextral component along the line of the Thrust due to thrusting oblique to the strike of the thrust sole. A more or less westerly directed thrust movement would be capable of producing clockwise rotation on more advances lobes of the overthrust mass (fig. XVI-10) whose sole strikes approximately 40° in this region.

B. Pseudotachylite and Flinty Crush-Breccia

In several places thick subhorizontal veins of pseudotachylite are exposed forming pavements of very closely jointed rock which tends to break out into lozenge shaped blocks. Striae which trend approximately E.-W. (fig. XVI-11) are common features and are probably due to later ice movement accentuating joint fractures, although Jehu and Craig (1923) state that most striae mapped by them trend north-west. The single undoubted example of glacial striae mapped in the course of the present investigation is on Orosay, Traigh Mhor (fig. I-4) and indicates a direction of ice movement from 100°.

The sole of the thrust surfaces comprises breccia cemented together with ultramylonite (pseudotachylite) and may be several feet thick. This flinty crush-breccia is admirably exposed in several parts of the field and invariably consists of angular fragments of various types of gneiss set in a groundmass of dark grey or black, green weathering pseudotachylite (fig. XVI-12).

In thin section the pseudotachylite ranges from dense brown to opaque, depending on whether or not the gneiss from which it was derived is dominantly quartzo-feldspathic or ferromagnesian. Small shattered chips and angular fragments of minerals and lenticular groups of minerals lie in an irresolvable, dense groundmass streaked with curved and discontinuous wavy fractures indicative of flow. Although the pseudotachylite can be seen to have penetrated even the finest fissures and to exhibit flow banding (fig. XVI-13) no evidence of recrystallisation in the form of spherulites has been found although these have been described from similar rocks at other localities (Kursten, 1957, Park, 1961, and Bhattacharjee, 1963).

Full descriptions of these rocks are already to be found in the literature (Jehu and Craig, 1923, Park, 1962 and Bhattacharjee, 1963) and nothing has been discovered during the course of the present work which would constitute a material addition to these.

Examination of orientated thin sections of flinty crush-rock and pseudotachylite have failed so far to reveal any evidence of either the sense or the direction of movement associated with the thrusting. It is reasonably certain that had conclusive evidence been obtained in even one locality then examination of several suitably oriented pseudotachylite veins and patches of flinty crush-rock might have revealed a movement pattern related to that obtained from tension gashes and to a shear system which could have been analysed in order to determine the true main thrust direction. Weathered gneiss at Grean which has been crenulated apparently by thrusting movement has given the clearest indication of the production of penetrative structures by thrusting.

XVII. FAULTING, JOINTING AND POST-LEWISIAN DYKE INTRUSION

A. Joints and Faults

Succeeding the main period of thrusting, and following at least one intervening period of normal faulting due to east directed tension, there was a return to conditions of compression in the same direction. Evidence for this is to be seen in the existence at Grean of structures which could arise only in consequence to normal faulting followed by reverse faulting (fig. XVII-1). The faulting is clearly not related to the main phase of thrusting, being more brittle in style and not associated with either flinty crush-breccia or pseudotachylite.

As a general rule the recognition of faults in the gneisses is very difficult because of the absence of marker horizons and lack of exposure sufficiently good to allow detailed mapping of different lithologies over extensive areas. Shatter belts on a larger scale in contrast form obvious topographical features and the position of most of the larger belts have been drawn on a map (Map. XI). To a certain extent it has been possible to determine displacement along some faults whose trends have been measurable from aerial photographs. The results obtained from examination of all photographs have been tabulated below (Table 8).

The tabulated results indicate that steep faults trending approximately east-south-east are sinistral in their lateral displacement and displace both east and south-south-east trending joints and Lewisian dykes. Approximately east trending faults tend to be dextral and displace both south-east and north-east joints and Lewisian dykes.

Table 8. Trends of faults and sense of their displacement

Trend	Displacement	Displaced structures	Locality: Aerial Photograph number
130°?	Sinistral	Joints trending 80°	1177
125-130°	Sinistral	Lewisian dykes. Joints trending 80°. Thrust outcrop	Gunnary: 3467
123°	?Sinistral	Lewisian dykes	Bruernish: 4486
East	Sinistral	Lewisian dykes	Balnabodach: 3484
120°	Sinistral	Lewisian dykes	3484
115°	Sinistral	Joints trending 170°	1165/1163
120°	Sinistral	Joints trending 170°	4464
115°	Sinistral	Joints trending 170°	4464
116°	?		3459
110°	?	Most joints trending 10°, 25°, 60°, 140° etc.	2171
170°	?	Joints trending 150°	2169
170°	?	Joints trending 100°	3471
95°	?	Joints trending 170°	4464
75°	Dextral	Joints trending 125°	4156
80°	Dextral	Foliation	Sourrival: 1163
90°	?Dextral	Most joints	4464
98°	?Dextral	Lewisian dykes	Balnabodach: 4484
98°	?Dextral	Lewisian dykes	Bruernish: 4486
100°	?Dextral	Joints trending 50°	3481

At only one or two localities in the field was it possible to map in a sufficiently detailed manner to determine faults and to some extent their displacement. On the coast east of Balnabodach and inland the presence of a large Lewisian dyke enabled mapping of the trend and probable sense of displacement of a series of approximately east striking faults. On Bruernish peninsula also, it was possible to map a number of faults because of the presence of Lewisian dykes. Some small faults with displacements of only a few feet were mapped on a scale of 1:2,500 at Bagh nan Clach near Scurrival.

Detailed measuring and statistical analysis of mesoscopic joints measured in the field has not been carried out. This is largely because the complexity of the geometry of the structure suggests that little would emerge from such an investigation which would also prove immensely time consuming. It is possible, however, that the greater proportion of joints which might have been associated with the more brittle phases of earlier orogenies would have been sealed by migmatization during later deformation. If this were the case most joints will be the product of the latest deformational phases; - the north-east folding and the thrusting. In support of this it is noteworthy that no curved joints have been seen.

Plotting of the trends of some of the larger vertical and steeply inclined joints measured from aerial photographs has been carried out for the gneiss of the overthrust mass (fig. XVIII-74) and for the gneiss west of the Heaval Thrust outcrop (fig. XVIII-75). The two plots do not differ significantly and the combined plots (fig. XVIII-73) show that the larger joints fall mainly into three groups trending 30°, 100° and 170°. (See Appendix I).

It is considered that the strong pattern of predominantly east trending joints may be related to late stage lateral tension normal to the compression associated with westerly directed thrusting. Steeply west dipping joints exposed in vertical E.-W. joints below the Thrust to the west of Heaval are considered to be due to tension set up by drag of the overthrust mass (fig. XVII-2).

The variation in spacing and regularity between joints developed in different lithologies is shown at several localities, particularly on the south-east coast (fig. XVII-3). Joints exposured on the shore near Eoligarry (fig. XVII-4) striking approximately 40° may be related to the north-east group of figure XVIII-48.

B. The Post-Lewisian Dykes

Post Lewisian dykes noted in the field (fig. XVII-5) have been mapped only because they are related to structural features like jointing and faulting, since, it is probably along just such surfaces of dislocation that they were emplaced during tension. They were presumably emplaced after the thrusting in all cases but evidence for only one or two cases has been uncovered to show that they actually transgress the Thrust outcrops in the present field (map I). A detailed study of the petrography has not been made, but they include quartz dolerites, olivine dolerites, crinanites, and lamprophyres and have previously been described by Jehu and Craig (1923).

General descriptions of representatives of the three commonest types examined in the course of the present investigation are as follows:-

1. Olivine Dolerite.

Dark and moderately coarse in hand specimen, this rock has been found in thin section to be porphyritic with large sub- to euhedral olivine phenocrysts showing marked serpentinization along fractures. Phenocrysts of sericite clouded, twinned feldspar are also common. The texture of the ground mass is sub-ophitic with small, pale brown crystals of augite partly enclosing, and partly interstitial between laths of labradorite. Tiny plates of iron ore are scattered throughout. Occasionally small fan-shaped aggregates of brown zeolite are present, and rarely, very small pleochroic emerald-green hornblende crystals have been seen. Needles of apatite complete the list of accessory minerals.

2. Quartz Dolerite.

Dykes of this nature tend to be generally larger and coarser-textured than the olivine dolerites, and often weather with a brown film.

Large subhedral zoned feldspars exhibiting micrographic intergrowths of dusty quartz are enclosed in an ophitic ground mass of anhedral neutral coloured augite, and feldspar laths. Flecks of iron ore are scattered throughout.

3. Crinanite.

This, like most of the dykes, is a dark, medium grained rock in hand specimen, but is invariably amygdaloidal.

It is porphyritic with moderately large phenocrysts of fractured olivine lying in a sub-ophitic groundmass of pale purple, faintly pleochroic, hour glass zoned augite and laths of labradorite. Serpentinization and chloritization of the olivines has taken place along fractures and crystal boundaries. Regular plates and specks of iron ore are disseminated throughout. Patches of clear, finely fractured analcite and amygdules of radiating and sheaflike groups of fibrous brown zeolite are scattered through the groundmass.

XVIII. STRUCTURAL ANALYSIS

A. Discussion

Structural analysis of systems of folds formed during anatectic conditions or conditions of incipient anatexis, or later modified by the effects of stress coupled with migmatization may be subject to severe limitations. The form of much of the folding exhibited by the gneisses in the Bagh nan Clach area leaves little doubt that deformation has taken place under conditions of plasticity and extreme viscosity so that deformation resulting from a single phase may have been, and indeed probably was, inhomogeneous. The lobate style of folding frequently encountered in this field is described by Carey (1953, p. 97) as follows:

> "The pattern of rheid folding in crystalline gneisses will be much easier to understand if it is realized that the whole fold does not advance simultaneously as is the case in shallow folding. First one lobe advances substantially and slows down or stops, next its neighbour, or another a little distance away, and so on, with the result that after a time the whole front has been advanced, although an original straight line is now highly indentate. The reason for this is that such rheid deformation occurs in a zone of active orogenesis, with granitization and hot emanations not far away. Now the viscosity of the rocks is as previously pointed out related exponentially to temperature. As the temperature gets higher, the fall in viscosity for a given rise in temperature becomes greater. Rocks, however, are very poor conductors, and most of the heat is brought in convectively, through interstitial vapours and gases. The rate of heating is therefore far from uniform and quite substantial differences of temperature may exist at no great distance if the permeability to the vapours is poor. The hotter zones therefore have appreciably lower viscosity and under the regional pressure advance diapirically ahead of the others, but in the general direction of the falling temperature gradient; this enables the ones left behind soon to overtake them".

There is little doubt that local inconsistencies in fold patterns would arise from deformation of this type although it is felt that extreme conditions of this kind would have had only local extent. In any case it was hoped that errors arising in consequence of this would tend to be offset by the employment of statistical methods using large samples, for the analysis of the structure. In this way local irregularities in the broad pattern would be absorbed into the overall structural picture. The results obtained in the main tend to support this belief. Errors arising from the unknown variability in significance of individual measurements because of poor exposure are expected to be eliminated by the same techniques. For example, on some small exposures it may have been possible to record on the map the orientation of only one fold axis but there may be several other closely spaced structures of the same orientation exposed at this locality, whereas in another place a similar record may represent only one or two parallel structures. Variation of this kind is unavoidable because of the quality of the exposures.

The contouring of most plots has been carried out using the grid method although in many cases the number of points is below that normally considered to be the acceptable minimum for this technique. The use of more accurate methods has not been generally adopted because the sharpness of patterns likely to be obtained would not be sufficiently great to warrant this. Furthermore, any such increase in resolution of the fabric pattern of rocks which have been so highly deformed would result simply in "empty magnification", thereby giving a completely false picture of the geometry and one of great apparent complexity.

Statistical examination on a macroscope scale of the structure in the Lewisian gneisses, besides being subject to the usually accepted drawbacks of sampling errors due to inadequate and irregular exposure, is made more difficult by the nature of the exposures. In most cases these are little altered surfaces smoothed by ice which except in a few places, have not suffered differential weathering and erosion. In consequence it is normally very difficult to determine much more that the attitude of the trace of linear and planar structures on the outcrop surface, and where the relief is low and exposure intermittent it must be admitted that the reliability of the structural data obtained is often of a low order. The impossibility of accurately determining the dip of the foliation proved to be one of the most disappointing features of the investigation. This is probably the greatest single drawback to the structural investigation in the present field, and in view of the extremely complex geometry, a very serious one, particularly as there are occasions when it is not only the degree of dip (or plunge) but the sense also which is in doubt. For this reason it is likely that less has emerged from the statistical plotting of structural elements than would normally be expected. Therefore, the purely statistical approach has been augmented by examination of field relationships between structures in different localities and consideration on the exposure of evidence, if any, for superposition. That this method is likely to be prey to a certain amount of subjectivity is fully realized and this has been brought home frequently in the field by the fact that the chronological order of the events listed in the tectonic sequence finally accepted has changed several times during the investigation. The determination of the structure in the Scurrival area by methods of statistical analysis combined with accurate mapping of form lines has been the most rewarding part of the present work.

A few days in the field were sufficient to show conclusively that the Isle of Barra, taken as a whole, represents a domain which is heterogeneous with respect to foliation and nearly all linear features such as fold axes and traces of axial surfaces (map I, figs. XVIII-1, 2).

B. Method

The systematic determination of areas which are homogeneous with respect to foliation and linear features was carried out by plotting of data from regularly spaced stations based on an arbitrarily located grid in the area west of the Heaval Thrust between Castlebay and Cuier (fig. XVIII-3). Detailed mapping of selected parts of this area has been done also. Plots of poles to foliation fold axes and β - diagrams from areas covered by individual aerial photographs have been made for the whole of Barra and these, the initial step in the present structural analysis, formed the basis of further detailed examination although they have not all been figured here. Equal area plots from this area are discussed in section XII, p. 107. Consideration of the small domains bounded by the two thrust outcrops resulted in simplification of the patterns of preferred orientation of structural elements but these still remain totally inhomogeneous, although patterns for folds with 100° trending axial planes show a tendency to strong concentration on either side of the thrust.

Analysis of the type undertaken is dependent on the fact that the structures considered are all (except for some folds of F_2 generation) of a small scale compared with the general attitude of the foliation and therefore their genesis is not associated with major foliation reorientation (fig. XVIII-4). Were this not the case, investigation of the tectonic history, even on this scale, could have been virtually impossible.

In the north at Scurrival the results of mapping form lines and marker foliation on a scale of 1:2,500 were used as a basis for subdivision into areas broadly homogeneous with respect to foliation and from these the attitudes of the fold elements and the form of the folds were determined.

C. Results

1. General.

Poles to foliation above the Heaval Thrust lie on a vertical girdle striking approximately 80° with a suggestion of dispersion on small circles about an axis plunging steeply east-south-east (fig. XVIII-5). A similar fan shaped distribution of poles would be obtained from refolding of the east limb of an approximately horizontal 170° trending fold about an axis plunging steeply east (fig. XVIII-6). A plot of poles to foliation below the Thrust shows a weaker girdle about an axis plunging gently to 350° and a strong maximum which like that on the plot of poles for the overthrust gneisses shows a fan shaped distribution. In this case there is a suggestion of crossed girdles rather than of dispersion about small circles (fig. XVIII-7).

The grouping of fold axes with east-south-east trends is not greatly intensified by subdivision into smaller domains and this suggests that, besides the fact that the degree of homogeneity has not been materially increased by subdivision, the 100° trending axes were amongst the latest developed. A plot of small fold axes in relation to foliation (fig. XVIII-8) has been made assuming rotation about vertical axes. This shows a slight concentration at the "north" and "south" parallel to the foliation suggesting that many of the axes measured are early isoclinal axes. All other axes show considerable spread with the exception of those trending at 100° which have been rotated into the "south east" quadrant. This tends to confirm the comparatively late stage deduced for these folds from field evidence of superposition (Section XIV, p. 142). There is a faint suggestion that a group almost perpendicular to the foliation represents an important fold direction imposed before major reorientation of the foliation to its present general attitude by F_2 folding (Section XII, p.107).

Rotation of small fold axes recorded east of the Thrust by levelling of the statistically defined 100° F_4 axis (fig. XVIII-2) to see if any pattern would emerge did not produce any appreciable increase in regularity of distribution (fig. XVIII-9) and this is considered to be due to the small size and the more open style so frequently characteristic of these F_4 folds. Rotation of these axes about F_4 to the horizontal resulted in grouping in clusters obviously related to F_1, F_2 and F_3 (fig. XVIII-9). The distribution of two north-east trending maxima on the contoured diagram of small fold axes for the domain east of the Heaval Thrust (fig. XVIII-10) and of an elongate subsidiary north-east trending maximum on the plot of all small fold axes measured on Barra (fig. XVIII-2) indicates distinctly a suggestion of rotation of these axes on a small circle girdle about an axis trending approximately 100°. The double concentration of the north-east axes (fig. XVIII-10) is due to dispersion about the 145° trending F_3 axes and the girdle about 72° is the result of the late north-east folding F_5. The greater density of attitudes of north-east plunging folds plotted from above the Thrust (fig. XVIII-10) as opposed to that of those plotted from below (fig. XVIII-11) is considered to be due to the fact that this structure was impressed on the fabric before F_2 Scurrival folding caused major reorientation of the foliation attitudes (Section XII, p. 107). Above the Thrust the strike of the foliation is constant and very regular (fig. XVIII-5) so that F_1 axial dispersion is at a minimum. Note that maxima for both F_1 and F_4 folds east of the Thrust are rotated clockwise by approximately 15° with respect to the corresponding maxima below the Thrust and this is considered to be due to rotation of the whole of the overthrust block (Section XVII, p. 169).

Plots of strike of vertical foliation taken from the map were made for the domains respresented by the areas east and west of the main Heaval Thrust (figs. XVIII-12, 13). The grouping on the plots reflects two principle structural features.

Vertical strikes measured for the whole of Barra show two distinct groups (fig. XVIII-14). One of these is in the form of a strong concentration in the region of 170° and therefore parallel to the trend of the Scurrival 350° plunging folds (fig. XVIII-10). The other is less distinct and forms a spread either side of 150°, which is the trend of sometimes moderately steep limbed folds associated with the Halaman Bay lineation (fig. XIII-1). The few measurements parallel to the north-east and east-south-east indicate that the styles of folding associated with these directions are, as a rule, of a more open shallow type. There is thus a reflection of the style of folding in the grouping of the strikes of vertical foliation.

A second feature which emerges from consideration of the strike of vertical foliation on either side of the Thrust is the distinct lack of 150° strikes on the east side. This may be due to the fact that the tendency for folds of this trend to form with moderately steeply dipping limbs would be less likely in foliation dipping fairly steeply to the east, with an average strike of approximately 170°.

The steep, 170° striking foliation is likely to have extered a very strong control over the attitude of potentially 150° trending, F_3 folds. Even if the later F_3 folds were not brought into complete parallelism with the 170° strike their attitudes would have been strongly modified so that the attitudes of their limbs would be indistinguishable from local variations in the 170° strike. The vertical foliation parallel to 170° is, of course, considered to have originated at the same time as the general 170° foliation strike due to major folding of the Scurrival F_2 style (Section XII, p. 107). A further possibility to account for the general absence of 150° vertical foliation east of the Thrust is that the overthrust sheet might originate from a region only slightly affected by the 150° trending Halaman style of folding of F_3. Before seriously considering this alternative, however, it would be necessary to have some indication of the degree of movement associated with the thrusting, and at present this information is not available.

Several combinations of structural data, other than those just discussed and those about to be discussed from the Castlebay to Cuier area, were plotted in an effort to determine whether or not additional information on the tectonic history of the gneisses could be obtained. The resultant patterns failed to add anything new and did not materially assist in the interpretation of the plots discussed in this section and for this reason they have not been included here.

2. Area between Castlebay and Cuier.

On the structural map of the area west to the coast from a line joining Castlebay and Cuier an arbitrarily located grid was marked (fig. XVIII-3). Structural data from within these squares was plotted on equal area projections and on the basis of the plots the whole area was then divided into domains approximately homogeneous with respect to foliation (fig. XVIII-3). It was found to be convenient to sub-divide the area of the grid initially into two smaller areas one of which, the area including Borve and Cuier, is homogeneous with respect to the foliation.

a). The Domains included in the Borve and Cuier area.

In the area north of Halaman Bay, combination of data was carried out in two ways, as groups of small domains and as individual domains, and the results compared with plots in which all poles to foliation and all small fold axes are recorded for the whole area. In addition, synoptic diagrams were prepared of β-diagrams and π s-poles from all domains in the area. Throughout this area the foliation S_1 is statistically homogeneous (fig. XVIII-15). β, and π s-poles (fig. XVIII-16) for each small domain all lie close to a great circle parallel to the projection of the average attitude of the foliation obtained from a plot of s-poles for the whole domain (fig. XVIII-15).

Poles measured from Domain I (fig. XVIII-17) lie on a small circle girdle whose axis plunges to the north-east. They thus define an axis of conical folding plunging towards approximately 40° and this is considered to be related to the final north-east folding, F_5 (Section XV, p.155).

Attitudes measured in Domain II (fig. XVIII-18) form a maximum plunging to the south-west which displays a tendency towards spread along a small circle centred by a north-east plunging axis.

Domain III poles to foliation (fig. XVIII-19) form a complex pattern through which several possible girdles could be drawn. This ill-defined group plunges to the south-west.

Attitudes from Domain IV (fig. XVIII-20) form a fairly strong concentration plunging steeply to the south-west, but showing a tendency towards N.-S. elongation due, in all probability, to late folding about 100° trending axes. There is also some dispersion on a south-east striking girdle, due probably to later north-east folding.

Domain V poles to foliation plot as a fairly regular maximum which again plunges steeply to the south-west (fig. XVIII-21). Again there is a hint of dispersion about a small circle girdle whose axis trending north-east, plunges this time to the south-west.

In the plot of poles to foliation recorded from Domain VI (fig. XVIII-22) a concentration plunging to the south-west is elongated on a north-east striking girdle.

A similar pattern emerges on the plot for Domain VII (fig. XVIII-23) but this time the concentration shows slightly less elongation.

A synoptic β -diagram prepared from great circles normal to the

S-pole maxima from each subarea, suggests that broad folding about a north-east axis has slightly affected the otherwise regular orientation of the foliation in this district (fig. XVIII-24). Similarly a β-diagram of foliation and a plot of small fold axes from Beinn Mhartuin both indicate that broad folding on a north-east trending axis has affected the gneisses (fig. XVIII-25).

A plot of approximately 60 small fold axes from the whole area shows a remarkably regular grouping (fig. XVIII-26). Maxima occur in three groups indicating that there are at least three groups of axes which plunge as follows: 10° towards 45°; 0° towards 148° and 10° towards 105°. There is a suggestion of spread of these groups along small circles about an axis trending about 60° (Section XV, p. 155). The strongest maximum of the small folds is that plunging towards 105° and this corresponds to the direction which is considered to be parallel to the penultimate period of open small folding (Section XIV, p. 142). The maximum plunging at 10° towards 45° is almost as strong and is thought to represent small folds of the very early north-east trend (Section VIII, p. 77), perhaps reinforced with some small folds associated with the latest north-east warping (Section XV, p. 155). A less pronounced maximum associated with a partial girdle trending 148° is regarded as representing the phase of folding responsible for the lineation at Halaman Bay and prior to that producing folds whose axes trend parallel to 100° (Section XIV, p. 142). Folds with 120° axial trend of F_2 phase

(Section XII, p. 107) are poorly represented in this part of the field.

b). The Domains in the Castlebay and Halaman Bay area.

The inhomogeneity of this domain with respect to foliation is immediately apparent (fig. XVIII-27). At the north end at Tangusdale the foliation dips moderately to the north and north-east on both sides of the Tangaval Thrust. Southwards to Castlebay the dip swings to the east-north-east (and occasionally west-south-west) and finally to the south at Castlebay. Just west of the Thrust north of Castlebay the foliation dips gently to the north-east and the south-west and in the domains north to the valley at Borve, the dip is to the west and north-west, contrary to the sense of the dip in the remainder of the region. The foliation in the domain, together with attitudes from adjacent sub areas, thus defines folds plunging to the north-north-west. These are considered to be moderately large isoclinal folds whose limbs lie parallel to the regional trend of the foliation (fig. XVIII-1) and which are similar in style to those exposed at the north end of Bagh nan Clach, (map II). Folds of this style have been mapped in detail on 1:2,500 at the Croig (map VI) and east of Tangusdale (map IV).

Poles to foliation plotted from Domain I produce a lobate pattern with two maxima (fig. XVIII-28). Through the lobes three girdles could be drawn with poles plunging at 28° towards 330°, 0° towards 114° and 32° towards 60°. This suggests the existence of three possible fold axes parallel to these directions.

Data from domain II plots to form a pattern through which a great circle girdle can be drawn with a pole plunging 4° to 154° (Section XIII, p. 134) and a small circle with an axis plunging at 18° to 114° (Section XIV, p. 142) (fig. XVIII-29). Faint dispersion about small circles whose axis trends north-east suggests late, slight folding about this direction (Section XV, p. 155). The intensities and natures of the sub-elements of the pattern tend to suggest that the 150° trend was the earliest, with later folding about east-south-east axes and finally warping about north-east trending axes. The few small fold axial orientations recorded show concentrations in the south-south-east, the south-east and the west-north-west and a group plunging at 40° to the south-west. These correspond very approximately to fold axial directions determined independently in the field (see p. 40).

Plotting of poles to foliation from Domain III shows a maximum with a concentric pattern and only a faint suggestion of girdling defining an axis plunging gently to the north-west (fig. XVIII-30). Small fold axes are concentrated in the north and east of the diagram.

Domain IV shows distinct girdling associated with a maximum (fig. XVIII-31). This defines an axis plunging at 15° towards 150° (Section XIII, p. 134). A less pronounced girdle can be distinguished which has a pole plunging at 15° towards 110° (Section XIV, p. 142). The lobate character of the pattern suggests dispersion on small circles centred in the south-east quadrant (Section XIII, p. 134). The axes of small folds lie in the south-east quadrant on a sinuous girdle dipping at approximately 20° to the east.

The maximum of domain VI shows distinct elongation into a girdle whose pole plunges at 4° to 143° (Section XIII, p. 134) (fig. XVIII-32). Lobes on the main group suggest small circle dispersion about a north-east trending axis (Section XV, p. 155). Small folds are concentrated in the east and south-east.

The plots of Domain V show the least regularity of pattern with suggestions of girdles with north-north-east trending axes and also of a small circle girdle about a south plunging axis (fig. XVIII-33). The irregularity was considered at first to be due to the fact that the data is from an area within the Thrust zone and probably comprising attitudes measured from isolated exposures in small dis-oriented thrust splinters (map I). However, the plot shows conclusively that measurements have been made on the limbs of a large early north trending isoclinal fold similar to those outcropping in Bagh nan Clach, and nearby at the Croig.

The fabric diagrams of each of the domains in the Halaman Bay to Castlebay area considered as a whole, although approximately homogeneous with respect to foliation, each show only a suggestion of homogeneity with respect to small fold axes. Faint concentrations suggesting agreement with fold directions and sequences deduced independently in the field do emerge, but it is doubtful whether these would have been of value in determining the tectonic sequence if considered by themselves. This is probably no more than could be expected from a terrain as highly complex as the one under consideration.

Data from the whole of the area between Castlebay and Tangusdale plotted on a single diagram provide no further information (fig. XVIII-27). Poles to foliation lie in an elongate maximum forming a broad girdle whose pole plunges at 5° to 142° and there is a faint suggestion of girdling about an axis plunging at 5° to 350° (fig. XVIII-27). Small fold axes lie in a sinuous girdle close to a great circle striking approximately parallel to that of the foliation poles and dipping at about 20° to the south-east (fig. XVIII-34). There is every indication that this represents clusters of fold axes of several generations repeatedly folded, because local curvature of the girdle is clearly related to oblique small circles. The distortion is probably due to folding of earlier axes about 100° trending F_4 axes and then later dispersion about north-east F_5 axes. The flattened S-shape (hysteresis curve form) of the girdles is very similar in style to the patterns obtained during early arbitrary subdivision of the area for plotting purposes (figs. XVIII-35, 36, 37, 38, 39, 40) and is the type of plot that could be obtained by cylindrical folding of an early fold direction about a plunging oblique axis.

Attempts have been made to reconstruct a possible sequence of folding of the kind likely to produce this type of orientation diagram but without notable success but a surface was constructed from the plot and drawn (fig. XVIII-41). It is thought that in this particular area the size of folds of various generations has been larger than in the north and all of about the same order so that interference effects have been more than usually pronounced. A β-diagram prepared from average attitudes of S from different small domains is no more informative (fig. XVIII-42), nor is a collective diagram of the poles to individual S-pole girdles (figs. XVIII-43).

The overall form of the structure here is thought to be controlled by intense, early 150° folding (Section XIII, p. 134) warped about a later north-east trending axis (fig. XVIII-41) (Section XV, p. 155).

Detailed mapping on the scale of 1:2,500 of small areas in the vicinity of The Croig and Rudha Glas, two parts of the present area, confirmed in one case the existence of moderately large isoclinal folds (maps: III, IV and VI) and plots of field data from these localities further confirm the ubiquity of the 100° F_4 fold trend (figs. XVIII-44, 45). Twenty small fold axes measured at Nask also show a strong grouping close to 100° (fig. XVIII-46).

The cause of the dispersion in trend of folds of F_4 generation between about 80° and 110°, apart from that observed at Halaman Bay to be due to curvature over later broad north-east plunging folds, is due to the fact that the axial planar trends are often slightly inclined to one another and associated with intersecting shear surfaces (fig. XIV-2). In this respect some of them (fig. XIV-13) possibly represent groups of conjugate folds of types similar to those described from North Norway by Ramsay and Sturt (1963). The folds at present under discussion are considered to be genetically different from the Norwegian folds in that the sense of asymmetry is the same in a given locality (figs. XIV-7, 13), and they are not always associated with shear, a mechanism that appears to be a later effect of folding in some cases in this field rather than the cause.

The intensity of the 150° style of small folding and lineation at Halaman Bay and Castlebay compared with other parts of the field is thought to be due in part to the fact that this area forms part of the remnant of a larger macroscopic 150° trending fold (See also section XIII, p. 134).

A comparison of styles of folds of different generations shows that as a rule, mesoscopic examples of these are distinctive enough to be separated in the field, after due allowance is made for variation because of location on the major structure (fig. XVIII-47).

3. Localities measured in detail

a). Localities chosen

Plots from individual localities where the orientation of several fold axes were measured in addition to those recorded on the map have been considered as a separate group. The results have been treated in much the same way as those from the area gridded between Guior and Castlebay but have the advantage of having greater statistical significance, particularly when considered in relation to the foliation whose variation in gross attitude at individual localities is only slight. Because of the comparatively large number of measurements for the number of localities considered, the results of an examination of the variation in attitude of various groups of folds from place to place and in relationship to the change in attitude of the foliation is likely to be significant.

Places at which detailed measurements were made are at the following localities: three exposures on the coast south of Bagh nan Clach (figs. XVIII-48, 49, 50), at Bagh nan Clach (fig. XVIII-51), on the coast south of Doirlinn Head (fig. XVIII-52), three exposures on the hillside immediately north of the secondary school at Castlebay (figs. XVIII-53, 54, 55), on the shore east of Ersary (fig. XVIII-56), on the slope of the south-west flank of Beinn Mhartuin (figs. XVIII-57), on Halaman skerry (fig. XVIII-58), two exposures at the west end of Halaman Bay (figs. XVIII-59, 60) and two exposures on the coast between Ard na Gregaid and Halaman Bay (figs. XVIII-61, 62). The attitudes of folds of open form were plotted separately from tight folds where these were readily distinguishable in the field. The larger more open folds have been marked on the plots as large solid circles, small tighter folds as large open circles and folds which have not been subdivided in the field are marked on the plots as small solid circles. Poles to foliation are indicated by dots and the approximate average of these as a dot within a circle. The plots are described in the figure captions.

b). Analysis of the results

The analysis of the plots was carried out in the following way:

To see first of all if there is an obvious constant relationship between the orientation of the fold axes and the foliation, a single synoptic plot of approximate averages of groups of fold axes was made in relation to the foliation. The foliation attitude selected is the average for the whole of Barra and the pole is marked as before with a dot inside a circle. Strong concentrations of fold axial plunges are represented by solid circles and diffuse groups by open circles (fig. XVIII-63). Any suggestion of grouping would thus imply that the gross orientation of the foliation is due to a very late folding which has also resulted in reorientation of the fold axial trends and plunges. The plot shows a fairly even spread of maxima in a gently east dipping girdle with very little tendency towards grouping, and very much less than is shown on a plot of the same approximate maxima in the orientation (fig. XVIII-64).

The faint suggestion of grouping at north, north-east, east-south-east and south east was checked by plotting individual axial plunges in relation to an average foliation attitude in the same manner as for figure XVIII-63 (fig. XVIII-65). The suggestion of several groups disappears immediately and most axes lie in a single maximum plunging towards east-south-east on this plot with the remainder lying in a gently east dipping girdle. Clearly the gross orientation of the foliation is not primarily due to very late folding since several generations of folds are known to exist.

A similar procedure was adopted in plotting all approximate maxima other than those plunging towards the east-south-east and the south-east in order to see if any or all of the remaining approximate maxima represent folds of the early north-east generation (fig. XVIII-66). In this case there is a suggestion of grouping in the north-east quadrant which is stronger than that shown in the plot of maxima in their true orientation (fig. XVIV-64). A plot of all fold axial plunges other than those trending east-south-east and south-east confirms this grouping in the north east quadrant (fig. XVIII-67). The group plunges more easterly than other examples considered to belong to the F_1 north-east generation but this might well be due to the average reference foliation orientation chosen. It appears then that the foliation attitude is due to earlier reorientation during major folding, probably during F_2, even though the variation in dip and strike is only slight and could well be expected to result from warping about F_5 axes. The plot shows decided curvature on small circles about a horizontal axis trending approximately 70° and is probably due to the effects of the late east-north-east warping of F_5. The same dispersion is very faintly suggested in the plot of figure XVIII-65 already described.

A further attempt was made to check the importance of late folding parallel to F_5 on the pattern of the plots obtained. The approximate maxima were plotted in a single diagram in their true orientation and the plots of those groups which showed a tendency towards elongation were crossed by a stroke parallel to this elongation (fig. XVIII-68). As before strong maxima are marked as solid circles. The plot shows a general elongation towards the north without any strong alignment on small circles about F_5, but on closer inspection it is seen that nearly all elongate trends lie on small circles about F_4 (dashed lines) or F_5 (dotted and dashed lines) and this is due to the fact that F_5 folding has not been sufficiently intense to modify the effects of dispersion of earlier folds during F_4.

Finally plots of fold axial plunges were made in their true orientation to see what sort of pattern would emerge. A diagram of all fold axes in true orientation shows a small north-north-east plunging maximum and two stronger maxima plunging just north of east and east-south-east within one section of an incomplete girdle linking all three maxima. The main break in the girdle corresponds to the trend of F_5 (fig. XVIII-69). The maximum plunging at 25° towards 12° is considered to correspond to folds of F_1 generation, rotated slightly by later folding. The two maxima plunging at 20° towards 80° and 15° towards 105° might be due to dispersion on small circles about F_5 or alternatively may be an expression of conjugate folding during F_4. On more than one instance in the field the style of F_4 folding suggests that folds of this generation are conjugate (figs. XIV-1, 2, 3, 13, 26).

To check further the possible effect of F_5 folding on the pattern of the fold distribution a composite plot was prepared from all localities having approximately the same foliation orientation (fig. XVIII-70). The plot obtained is substantially the same as figure XVIII-69 so that the pattern has clearly not been greatly affected by F_5 reorientation. The east trending double maximum could be explained without reference to a conjugate fold origin, however. If the east-north-east group is rotated to a horizontal east trend about a level F_5 axis then the east-south-east group moves to a position with a west-north-west plunge; a possible position on the opposite limb of a large fold for structures of the same generation as the east-north-east trending folds.

To determine whether or not the north-east group on the plots of figures XVIII-69 and XVIII-70 are early or late structures, the F_4 group was levelled about F_5 to see if the north-east group would show evidence of elongation along small circles about 100°, parallel to F_4 (fig. XVIII-71). The diagram shows some suggestion of small circle dispersion about an 80° trending horizontal axis. This is probably a resultant due to rotation about both F_4 and F_5 axes and suggests that the north-east trending axes are earlier at least, than F_4.

Finally a β-diagram was prepared of the foliation from the three adjacent exposures south of Bagh nan Clach to see if the pattern obtained would confirm the plots of fold axes from the same locality (fig. XVIII-72). Groups which plunge at approximately 35° towards 20°, 20° towards 80° and 5° towards 120° lie in girdle dipping at 45° towards 40°. The strongest maximum is that plunging towards 120° and the groups plunging at 25° towards 40° and 30° towards 60° are very much fainter. In view of the distribution of β -groups of varying concentrations, the diagram suggests very strongly that there has been a rotation of approximately 15° to 20° in a clockwise direction due probably to thrusting, and support for this is seen in the presence of several prominent shear surfaces which outcrop at this locality. A rotation of the whole plot in an anticlockwise direction through 15° to 20° results in the maxima trending approximately parallel to the present fold axial trends of F_1 (30°), F_2 (355°), F_3 (145°), F_4 (100°) and F_5 (60°), and furthermore means that the relative intensities of these maxima is of the correct order.

4. Joints.

The single structural feature which might be said to be statistically homogeneous throughout the whole island is vertical and subvertical jointing and the trends of this have been plotted directly from aerial photographs (fig. XVIII-~~72~~73). All the measurable trends of joints from aerial photographs were marked on a 180° section of a circular plot and these show a surprisingly regular grouping into three maxima at approximately 30°, 100° and 170°. The plot thus displays orthorhombic symmetry. There is no significant variation between the areas east (fig. XVIII-73 14) and west (fig. XVIII-~~74~~ 15) of the

Heaval Thrust although there is ample evidence from plots of attitudes of small fold axes to suggest rotation accompanying thrusting. Therefore the joint pattern obtained could be interpreted as a group of 100° striking tension joints and associated symmetrically disposed oblique shear joints due to west directed compression associated with the Thrust. It agrees also with the direction of thrusting deduced in the field from sigmoidal tension gashes exposed in vertical joint faces on the south-west flank of Heaval (fig. XVI-5). The one serious objection to this interpretation is that the angular separation between the tension and shear joints is too great and this suggests that the fractures measured are related to the stress field responsible for F_4 folding. In this respect the angular agreement is very close. The tension joints parallel P_{max} would lie at 10° between the concentrations representing the shear joints and the 100° trending joints would be axial planar, representing late joints opening with elastic rebound after release of the 10° compressive stress responsible for F_4 folding.[12.]

Ideally, joints related to sub horizontal thrusting should show axial symmetry modified by gravitational effects depending on depth of burial. The tension joints being radially disposed and the shear fractures tangential to a conical surface, but only the steeper members of the group would form distinctive features on aerial photographs (fig. XVIII-75).

The pattern of jointing is closely similar to that figured by Kursten (1957) for joints associated with mylonites from the Isle

[12] Hence curvature at Allasdale of 30° - N. See Addendum p. 141.

of Stuley, South Uist. But Kursten implies that the mylonites and their jointing are not associated with the main period of thrusting (Kursten 1957, p. 18).

5. Conclusions.

Systematic investigation of the structure of the Lewisian Gneisses, of the Isle of Barra at least, by the usual techniques of macroscopic statistical analytical methods alone is not likely to reveal an unambiguous solution to the history of tectonic events. It is felt, however, that further examination of carefully selected domains might extend and modify the information so far accumulated, although this technique is in itself potentially highly subjective. The limiting factor in any investigation in the present field is the exposure which, except on the coast, is rarely of acceptable standard. In spite of this it is hoped that further work, extended if possible to the other islands of the group, both to the south, and north to South Uist, using the present results as a basis will yield further information regarding the tectonic history of these extremely interesting rocks.

D. Structural Comparison with other Lewisian Terrains

One of the factors influencing the choice of field for the present work, by its very nature potentially somewhat subjective, was its isolation from other Lewisian Terrains. Thus it was hoped that, although little published work of a purely structural nature is available on these rocks anyway, the investigation would be less likely to be influenced by preconceived ideas of tectonic history. Therefore any comparison with other localities, particularly those on the mainland, is regarded as very tentative indeed, especially as the findings of other authors are by no means always clear.

Kursten (1957) working in the Outer Hebrides to the north of Barra concludes that the first recognizable phase of metamorphism was one of high grade, in the granulite facies with B-axes associated with this phase possibly plunging now to the south-west and south-south-west. These directions may be equivalent to the early north-east direction deduced in Barra (or north plunging Scurrival trend) although some lineations in South Uist trend 150°, parallel to a similar lineation at Halaman Bay. A second regional metamorphism associated with metatexis formed almost non-foliated granite gneiss. The trend only of these rocks has been determined as south-east with very steep dips. The age of associated acid pegmatites of South Harris is given as 1.1×10^{6} years. This trend is perhaps equivalent to the present 150° axial trend of Barra. Later deformation resulted in the formation of mylonites with 70° trending B-lineations (? equivalent to the late north-east fold directions of Barra) and later secondary 3° trending fold axes associated with thrusting suggest movement from just south of east parallel to that deduced for thrusting on Barra. The earlier "dry" metamorphism associated with charnockitic rocks is equated with Sutton and Watson's (1950) Scourian metamorphism and the younger "wet" metamorphism with the Laxfordian.

Dearnley (1962) lists three periods of folding for the Outer Hebrides north of Barra; i) Early granulite facies metamorphism and associated folding not further described but equated with the Scourian phase of Sutton and Watson (1950); ii) Following intrusion of basic dykes, a south-east folding and granulite facies metamorphism; iii) north-east folding, injection and retrogressive metamorphism. Phases ii and iii are equated with the Laxfordian. The last two of these phases may correspond in part to the 150°, and late north-east trending fold phases of Barra. After allowing for sinistral movement of 77 miles on his postulated Minch Wrench Fault, Dearnley equates the gneisses of Barra below the Thrust (South Uist to Barra Head) with those of the mainland from Loch na Sheallag southwards to Loch Torridon. This comparison is based on lithology and structural style and, as has been shown in the present work, must therefore be open to criticism. The gneiss east of the Thrust is not correlated with the mainland. The persistent west-north-west plunging minor folds and lineations noted in the "Central Zone" (North Uist and Benbecula) lie parallel to the ubiquitous east-south-east F_4 folds of Barra but the significance of their persistent trend in an area of variable strike is apparently overlooked by Dearnley since it is not noted as an important late phase of folding. It is possibly that some, at least, of the east-south-east and south-east trending axial planar traces figured by Dearnley on his map from the Outer Hebrides and the Scottish Mainland are genetically related to the F_2 folding of the present field.

In the absence of radiometric ages for the rocks of the present field and detailed descriptions of the structure from other localities it is not felt that attempts at correlation with other areas at this stage would be particularly valuable.

XIX. MIGMATISATION

A. Pegmatite Veins

Migmatization and the production of segregations and coarsely crystallized veins predominantly of quartz, oligoclase and orthoclase with a little hornblende, biotite or magnetite has presumably proceeded since the first orogeny, probably soon after the development of the initial banding, until some time prior to the latest phase of thrusting. Evidence for early anatexis and vein injection lies in the existence of tightly appressed, isoclinal, quartzo-feldspathic folds parallel to the foliation at various localities such as Tangusdale (fig. V-4) which are thought to be contemporaneous with the earliest recognizable isoclinal folding noted in the outline of sequence on page 40. Very large quartzo-feldspathic pegmatite bodies like those of South Harris have not been observed, the largest seen is a 100° trending vein tapering from a maximum of 50 yards wide west of Balnabodach and veins up to 8 feet wide at the south-east end of Leenish (fig. XIX-1) and the eastern end of Bruernish, the former trending north-east and the latter almost due east.

The distribution of pegmatites seems to be just as common in quartzo-feldspathic, as in ferromagnesian gneisses, although trans-gressive bodies tend to be more conspicuous in the later lithology. Quartzo-feldspathic material also tends to concentrate in low pressure areas in hinges of basic folds and on the "lee side" of these bands.

Undoubtedly there have been many periods in the history of the Lewisian Gneiss which is exposed on the Isle of Barra when anatexis, produced migmatites and associated pegmatites. Although there is ample field evidence to suggest that the remnants of many of these phases are still preserved in the gneisses as cross-cutting pegmatites and dykes (map IX), the absence of age dating results in a lack of conclusive proof of the number of, and chronology of these phases. Field evidence suggests, however, that periods of fold formation and anatexis are closely interrelated and the fact that rectilinear pegmatite veins frequently occur with trends close to those of traces of fold axial surfaces suggests that their emplacement has been controlled in many cases by fractures parallel to these structural surfaces. On the assumption that this control has in fact been a decisive factor in pegmatite emplacement (and in the absence of radiometric age determinations, there is little else in the way of evidence to indicate the age relationships of the various pegmatite intrusions) an attempt has been made to use cross-cutting relationships of pegmatite veins, dykes and folds as additional evidence in the determination of the structural history of the Lewisian Gneiss. The less likely possibility that veins may be injected along planes of weakness inherited from deformations earlier than that immediately prior to anatexis cannot be ruled out, however.

Throughout the field there is good evidence to give an indication of a general sequence of events in the history of the genesis of migmatite and its subsequent emplacement. Quartzo-feldspathic intrusions vary in form from large irregular pods and lenses with diffuse margins and narrower lenses with fairly well defined margins to sharply cross-cutting, tapering or parallel sided rectilinear veins of widths ranging from 50 yards (fig. XIX-1) down to an inch or even less (fig. XIX-2). Some, like that at Bagh nan Clach (map II) and east Leenish are homogeneous in composition (fig. XIX-3) whilst others like another vein at Leenish (fig. XIX-1) are distinctly banded and suggest multiple intrusion to form composite dykes of white quartz bordered by pink feldspar.

The pegmatite veins have been subdivided into three age groups distinguishable in the field by their appearance. The earliest veins are quartzo-feldspathic in composition and contain dark grey feldspars with a slightly waxy appearance which tend sometimes to make the pegmatites look like breccias when seen from a distance. Blocks of pegmatite from this group have been seen around which the foliation curves parallel to the margins, showing that they have been subjected to deformation subsequent to their emplacement. In this respect they resemble some of the blocks of basic gneiss in deformed banded quartzo-feldspathic gneiss (fig. XIX-26). Later pink feldspathic pegmatites are usually more obviously cross cutting and are the commonest type seen in the field, often penetrating the gneisses parallel to axial planes of structures ranging in age from F_2 to F_4.[12] These are probably the products of several generations of migmatite. The youngest of the three groups are white quartzose pegmatites which normally form transgressive bodies but which often lie parallel to the foliation. Their age relative to the pink feldspathic pegmatite veins can be seen at Leenish where a white pegmatite has been injected along the centre of an earlier pink feldspathic pegmatite vein (fig. XIX-1). The white pegmatites are among the largest of the quartzo-feldspathic intrusives and large examples of these outcrop west of Balnabodach and on the north-east shore of Bruernish peninsula. It is hoped to be able to verify, or otherwise, this chronological subdivision of the veins by radiometric age dating of samples from each of the three groups at some future date.

It is more than likely that the complete range of anatectic environments exhibited by present exposures is probably representative of conditions obtaining at various levels during different orogenies rather than a complete picture of the range of environments during only one or two phases of deformation. In several cases exposures suggest that anatexis and mobility have resulted in only very slight movement of material, and time and again the appearance of the gneiss

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[12] At the south end of the beach at Mingulay Bay pink pegmatites are cut by pseudotachylite. Both the pegmatite and the pseudotachylite are cut by F_3 150° trending lineation. A few hundred yards to the south rocks at the back of a small beach expose both early dark grey pegmatite and later pink pegmatite.

is such as to suggest incipient anatexis, with blurring of foliation and the suggestion of a tendency towards homogeneity of texture.

The development of ptygmatic folding such as that at Bagh nan Clach (fig. XIX-4) appears superficially to have resulted from injection of a barely fluid sheet of quartzo-feldspathic material into more or less fluid intermediate gneissose material in the manner suggested by Wilson (1952). On the other hand it is more likely that structures of this type have been derived from originally planar and nearly planar quartzo-feldspathic sheets which have been deformed by later orogeny while they and the surrounding gneisses were plastic (figs. XIX-5, 6). It is difficult to account for the form of some of the ptygmatic folds by shearing since they are so irregular in form, although specimens of an irregular ptygmatic type of vein, which is obviously the product of oblique shear have been collected from Bagh nan Clach (fig. XIX-7). In this respect these folds do not correspond to the folds described by Dietrich (1961) which are said by him to have developed in a passive host.

Migmatisation and pegmatite injection have continued right from before the earliest folding recognized here through to some time after the formation of the E.-W. striking septa, because ribs can be seen to have been transected and obliterated by oblique pegmatite veins and pods (figs. XIV-24, 29), possibly injected during, or soon after, the phase of late north-east folding.

D. Migmatisation of Basic Gneisses

The common association with basic gneisses (figs. XIX-8, 11, VI-3), seems to suggest that as conditions for migmatisation become critical slight variation in pressure was sufficient to "flash" the incipient migma to a fluid. Situations where pressure was prone to local variation were most likely to occur in the immediate vicinity of basic gneisses which remained more rigid than the surrounding rocks during deformation. Therefore, it is likely that considerable pressure differences could have been in existence on different sides of suitably orientated basic layers. Good evidence for this condition is seen in the difference in degree of pegmatite development on either side of basic bands (fig. XIX-9) and boudins such as those on the west side of Ben Scurrival (fig. IX-5). Here, on the east side of the boudinage the foliation, although somewhat faint and from its texture suggesting that it had approached a fluid condition, is still quite distinct with discrete folia still preserved. Nevertheless, on the other side of the boudins (only one or two centimetres away) where it appears that pressure was lower, because the foliation in the east side is buckled into the gap between the boudins, all trace of foliation is lost and a stream of pegmatite up to three feet in width appears to have flowed through and away from the separation between the boudins. This appearance is, however, in all probability due in part to accumulation of migma in an area of comparatively low pressure resulting from the bending of the series to form a curve concave to the right side (i.e. the east side) of the boudins in the photograph (fig. IX-5). The gneiss surrounding the basic layers being in a fluid state thus flowed a short distance through the gap between the boudins towards the left. The boudins had presumably already reached a form and orientation similar to that at present since enclosing foliation contours the existing shape of the structures.

An alternative possibility is that the gneiss was rigid enough for tension fractures to open up, with subsequent movement of volatiles which produced fusion along either side of the fracture so that slight later, or concomittant, movement was sufficient to destroy the existing structure in the migmatized banded gneiss in the zone shown in the picture. Certainly there is a suggestion of dextral movement, perpendicular to the foliation which has produced a type of drag folding and appears to have affected the boudins very slightly causing some rotation of individual blocks. The sense of this movement agrees with that found to affect boudinage (fig. IX-3) and 100° septa alike (fig. XIV-23) throughout the field. One or two exceptions are to be found such as the boudins exposed on Rudha Mhor above Brevig (fig. IX-2).

The effect of migmatization on basic gneiss appears to have been a mechanical interfingering coupled with removal of quartzo-feldspathic material in the immediate vicinity of the junction between the migma and the host rock to produce a darkened rim (fig. XIX-10). In the figure the darker rims on the basic gneiss show particularly well in line with point of the pencil.

On a larger scale anatexis of large basic masses produced a mouldlike effect (figs. XIX-11, 12) in the rock, with larger patches of migmatite "swirled" between the partly assimilated amphibolite block veined by smaller anastomosing veinlets of migma. Field evidence suggests that continued attack by migma produces an agmatite (fig. XIX-13) and ultimately a grey mottled gneiss of a kind similar to that which lies beneath the pencil in figure XIX-14, forming a broad band to the right of the interface between migmatite and amphibolite. This results in a rock of the kind shown in figure XIX-15 which shows an agmatite in an advanced state of anatexis which subsequently has been intruded by basic dykes. The whole has been sheared and probably subjected to further anatexis during a later orogeny. Figure XIX-16 illustrates a similar relationship with a later grey intrusion in the left of the picture. The end product of continued anatexis of basic gneiss is envisaged as a coarse mottled intermediate gneiss similar in appearance to hornblende gneiss which is exposed at Ersary (fig. XIX-17).

The extreme resistance of basic gneisses to breakdown during migmatization is clearly shown by the basic dyke of figure XIX-18 in which the margins of the remnants which are separated by migmatite but still parallel, are quite sharp and show no sign of fraying or breakdown by ichors. In many cases the more acid gneisses on the other hand have been rendered almost completely homogeneous by anatexis and it is only the presence of faint remnants of basic bands which enable the structure to be elucidated (figs. XIX-19, 20).

In other cases the quartzo-feldspathic material of basic gneisses has segregated into larger masses within the basic gneiss to give a mottled effect which may, if conditions persist sufficiently long become extremely coarse. Fine examples of segregation during 'stewing' of the gneiss whilst undergoing anatexis can be seen in the coarse hornblende crystal aggregates intermingled with pink quartzo-feldspathic gneiss on the south coast of Bruernish (fig. IX-13), on Leenish and on the east coast at Ersary (fig. XIX-21). Hornblende crystals have reached sizes of up to an inch and more in length under prolonged conditions of this nature. The largest single crystal observed is a 5" x $3\frac{1}{2}$" feldspar augen in medium grained quartzo-feldspathic gneiss at the north end of the west shore of Brevig Bay.

Although mechanical non-penetrative breaks in the gneiss to a large extent must have channelled the "fluids" producing anatexis, field evidence other than the darkening of the rims of basic "xenoliths" (fig. XIX-10, 26), suggests that migmatisation moved in waves through the gneisses as a series of fronts which were significantly retarded only when they met basic gneisses during which time breakdown of the host rock proceeded along an irregular interface essentially parallel to the original contact between the basic, and surrounding quartzo-feldspathic gneisses (fig. XIX-22). In the figure the front clearly advanced on a surface slightly oblique to the foliation since incipient migmatization is evident on the far side of the basic band whereas the margin of the thinner amphibolite layer further away is only very slightly affected (fig. XIX-23).

The effects of anatexis on amphibolite cross-cut by a Lewisian dyke can clearly be seen in figure XIX-24 where the migmatite front evidently moved from the top of the picture along the foliation until it met the cross cutting dyke. Its progress was accompanied by the stoping off of blocks of amphibolite with diffuse margins and assimilation of these until only faint remnants like those to the left of the pencil remained. The effect of anatexis on the dyke on the other hand has been to attack it along sharply defined lobate boundaries and even the small blocks stoped off have retained clear cut margins. Similar larger blocks (fig. XIX-25) result in the formation of tectonic inclusions (Rast, 1956) or "fish" (McIntyre, 1951).

Other examples of stoping and floating off of isolated blocks of basic hornblende gneisses can be seen in Bruernish peninsula (fig. XIX-26). In this example the foliation in the basic block runs from bottom right to top left and clearly stands at a high angle to the surrounding foliation on which is slightly folded. This is a fairly clear indication that anatexis which has blurred the banding in the acid gneiss and detached the basic block has not resulted in purely replacive migmatisation *in situ*. In figure XIX-27 the front has arrived at both sides of the basic layer at approximately the same time and migmatisation (and agmatization) is equally well developed in each side. Figure XIX-28 shows clearly the difference in the resistance to attack by anatexic effects of basic, as opposed to intermediate, bands in the gneiss. At the top centre the relationships between the darker basic bands in the enclosing intermediate gneiss can be seen. Immediately to the left of the pencil is an area where all the intermediate material has been migmatized whilst the basic remnants float almost unmodified, apart from rounding of the edges and coigns. This relationship obtains in spite of the fact that at the top of the picture the darker amphibolites and the grey gneiss from which they protrude were clearly being affected together by anatexis along their margins. This suggests that the intermediate layers had already reached a state of incipient mobility and would have broken down completely had conditions remained the same for a little longer or had the reaction proceeded to a slightly more advanced stage.

Figure XIX-29 shows basic remnants in a homogeneous quartzo-feldspathic gneiss, again with darker rims. In this case it was possible to obtain specimens and cut thin sections and it was found that the rims on these nodules comprise a higher relative proportion of biotite to hornblende and pyroxene than at the centre. This suggests that the dark rims then are due in this case to introduction purely replacive migmatisation *in situ*. In figure XIX-27 the front has arrived at both sides of the basic layer at approximately the same time and migmatisation (and agmatization) is equally well developed in each side. Figure XIX-28 shows clearly the difference in the resistance to attack by anatexic effects of basic, as opposed to intermediate, bands in the gneiss. At the top centre the relationships between the darker basic bands in the enclosing intermediate gneiss can be seen. Immediately to the left of the pencil is an area where all the intermediate material has been migmatized whilst the basic remnants float almost unmodified, apart from rounding of the edges and coigns. This relationship obtains in spite of the fact that at the top of the picture the darker amphibolites and the grey gneiss from which they protrude were clearly being affected together by anatexis along their margins. This suggests that the intermediate layers had already reached a state of incipient mobility and would have broken down completely had conditions remained the same for a little longer or had the reaction proceeded to a slightly more advanced stage.

Figure XIX-29 shows basic remnants in a homogeneous quartzo-feldspathic gneiss, again with darker rims. In this case it was possible to obtain specimens and cut thin sections and it was found that the rims on these nodules comprise a higher relative proportion of biotite to hornblende and pyroxene than at the centre. This suggests that the dark rims then are due in this case to introduction of potash and break down to a lower metamorphic grade of the mineralogy by the retrogressive effects accompanying the process of anatexis. The same sort of effect can be seen adjacent to very thin migmatite veins transecting a broad hornblende granulite dyke on Leenish (fig. XIX-2). Here although the veinlets are only an inch or less wide the darkened altered band is easily as wide as, or of even greater width than the vein.

Wherever strong cross-cutting relationships are evident between quartzo-feldspathic veins and basic gneisses the effect on the invaded basic rock compared with the boundary effects on basic gneisses in regions of anatexis, can as a rule, be seen to be relatively slight (fig. XIX-30). This is well shown in the fine, narrow quartzo-feldspathic veins intersecting the Leenish granulite dyke (fig. XIX-2) which, although transgressive in nature, are clearly the result of emplacement in, or close to, an anatectic region. They have distinct dark selvedges indicating considerable reaction between the migma and the intruded basic gneiss of the granulite dyke and in the field the state of the surrounding more quartzo-feldspathic gneisses bears witness to the fact that these have been subjected to considerable migmatisation.

C. Migmatisation of Acid and Intermediate Gneisses

The effects of anatexis on more acid and intermediate gneisses characteristically produce a spread of migmatisation with very diffuse boundaries through the gneiss. Margins of zones of anatexis in acid and intermediate gneisses grade imperceptibly into the surrounding banded country rock without any evidence of a sharply defined contact (fig. XIX-31). The photograph of figure XIX-31 is taken across the zone of gradation between relatively coarse quartzo-feldspathic pegmatite in the foreground to banded, slightly migmatized quartzo-feldspathic gneisses in the background. The foliation, although faint in this area can be seen to lie parallel to the hammer handle but nearest the camera all trace of banding has been obliterated.

Destruction of foliation appears to be preceded in many cases by growth of feldspar porphyroblasts (fig. XIV-3). These augen frequently coalesce to form long thin feldspathic and quartzo-feldspathic lenses. Augen of this type have been seen in unbanded intermediate grey gneisses on the roadside at Skallary also, and in well banded gneisses on the west flank of Heaval above the Thrust, and on the shore at Brevig.

When conditions of anatexis persist for sufficiently long, large patches of gneiss become migmatized leaving only diffusely bordered, isolated septa and pillars of foliated gneiss projecting into a more or less homogeneous migmatite (fig. XIX-32). Mobilization occurs later and migmatite is injected into low pressure areas in the hinges of folds and in tension fractures and the consequent movement of migma may raft along partially migmatized blocks of country rock (fig. XIX-33).

The relationship between fold periods and phases of anatexis and migmatization is not one which can be clearly determined. That there is some relationship between fold axial directions and trends of zones of migmatites and quartzo-feldspathic veins is readily seen in the field (figs. XIV-7, XIX-34) but whether the genesis of the migmatite is a consequence of, or is related to, the forces producing the folding is not readily determinable. A plot of trends of elongate pegmatite bodies further suggests some correlation along these lines (fig. XIX-35). In that conditions favourable to the formation of migmatite could result in a very high degree of plasticity, and perhaps in extreme cases, fluidity of the country rocks it seems likely that most folding of the styles recognized in the field could not have taken place concurrently with anatexis. Although admittedly a fairly high degree of plasticity has obtained during folding in many cases this probably has not reached a degree approaching the state of fluidity, or near fluidity which was extant during anatexis. A more likely state of affairs is that migmatization followed fronts moving upwards immediately after folding and accompanied by migma injection moved preferentially through quartzo-feldspathic gneisses and followed paths of mechanical weakness like fold axial planes and tension fractures formed during the release of stresses which caused the folding.

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LIST OF TABLES AND MAPS.

APPENDIX I - NOTES ON MAPS

Map I

Because of the great detail on this map it has been necessary to reproduce it on approximately the same scale as the original. To avoid confusing the map with a great abundance of detail, only representative structural data is included in those areas dealt with on maps II, III, IV, V, VI and VII. For the same reason only very large post-Lewisian dykes have been drawn in. The Lewisian dykes on the end of Leenish (map IX) are omitted also because of the scale. Faults have been included only where their displacement has been determined from field mapping. Other shatter belts and faults are shown on Map XI, as has the approximate lower (western) limit of the Thrust belts. Form lines have been omitted for obvious reasons except in the Scurrival area where the structure has been proved.

Maps II and VII

All measurements of attitudes of foliation and linear structures have been included on this map except for those made in the areas dealt with in detail (section XVIII, C, 3, p. 192). The basic interfoliated gneisses have been denoted simply as amphibolite and marked as solid black on the map. These include basic gneiss of varying grain size ranging from almost pure hornblende gneiss to rocks whose dominant mineralogy includes combinations of dark green hornblende, pale green clinopyroxene, andesine and sometimes garnet. The quartzo-feldspathic gneisses have not been subdivided and are not ornamented. Unexposed areas are indicated by the absence of orientation symbols.

The form of the structure shown by the form lines on Fiary has not been proved.

Map III

The apparent closed structure elongated parallel to the south-south-east seen on the aerial photographs which prompted this detailed map clearly does not exist. What can be seen is the swing in attitude of folds of F_3 and F_4 generation due to dispersion about late F_5 axes.

Maps IV and VI

These two adjacent areas have been combined on the one sheet. Only the northern area proved to have large mesoscopic isoclinal folds of the kind suggested by the outcrop pattern on the aerial photographs. In the southern part of the map at The Croig there is a suggestion from form lines in the south-east corner of an isoclinal fold closing to the north-north-west.

Map V

The general south-east trend of F_3 small folds and lineation with slight local deflections can be seen, particularly in the southern part of the map where all earlier structures have been warped over a broad F_5 east-north-east trending dome. A photograph of a small part of the south-eastern part of this area is shown in figure XIII-1.

Map VIII

This map shows the position of the arbitrary grid subdividing the domains from Borve to Cuier and Halaman Bay to Castlebay west of the Heaval Thrust. The small diagrammatic plots indicate the form of the plots from each small sub-area which have been combined in each of the areas from Borve to Cuier, 1–VII and Castlebay to Halaman Bay 1–VI and discussed in the text (Section XVIII, p. 175).

Map IX

This is a sketch map drawn as accurately as possible on enlarged aerial photographs on the scale of 1:625 but is not exactly to scale. The geology is superimposed on an enlarged topographic map showing the lines of high and low water marks. The numbers on the dykes refer to the numbers of the specimens collected and noted in the text. The attitude of the foliation is diagrammatical only and is based on the average for the northern part of this locality.

Map X

This form line map has been scaled down from two sheets on the same scale as Map I from which it is derived. Except in the north at Scurrival the structures suggested on the map have not been proved.

Map XI

This map is a compilation of the trends of the larger, more prominent shatter zones determined from the aerial photographs and includes the larger of those used for the plots of figures XVIII–48, 49 and 50. Included also on the map are the outcrops of the base of the two larger thrust segments and the approximate lower limits of their associated soles of pseudotachylite and flinty crush-breccia.

APPENDIX II - GLOSSARY

Domain (Fabric Domain) (Turner and Weiss, 1963, p. 20).

The term domain is here used to specify any finite three-dimensional portion of a rock body that is statistically homogeneous on the scale of the domain. Domains are usually outlined by boundaries that are natural surfaces of major discontinuity in structure or composition. A portion of a particular domain may be termed a subdomain.

Fabric (Turner and Weiss, 1963, p. 19).

This is used to denote the internal ordering of the geometric and physical spatial data in an aggregate and is, in the general sense, considered to be of infinite extent.

Form Surface (McIntyre and Weiss, 1956, p. 149).

Form surfaces are surfaces statistically parallel to the foliation at any point and although they do not necessarily correspond to any particular band or layer in the series they still represent the form of the structure concerned. (Strictly this is a descriptive term referring to statistically defined foliation but it is useful when referring to the geology of intensely deformed rocks like gneisses).

Homogeneity (Structural Homogeneity) (Turner and Weiss, 1963, p. 16).

Is taken to mean spatial uniformity of the internal constitution of the body of rock under consideration and is used in the present work with reference to rock bodies of all scales; microscopic, to tracts measurable in square miles (strictly cubic miles since the investigation is a three dimensional one). A body may be said to be <u>strictly homogeneous</u> if any two identically oriented equal-volume units or samples are identical. In nature discontinuities and irregularities occur on a small scale, so that irrespective of the size of the unit chosen no body can be regarded as strictly homogeneous. On the other hand, units can be chosen on such a scale as to contain representative distributions of any heterogeneities present in which case they are statistically identical or <u>statistically homogeneous</u> on the particular scale chosen. Thus the scale of the investigation has an important bearing on the degree of homogeneity and a homogeneous body on any particular scale can appear heterogeneous if subdivided into units of a smaller scale and may be either homogeneous or heterogeneous when considered on a larger scale, e.g. a layered igneous rock considered respectively as a microscopic sample from a layer; a hand specimen from a layer; a larger specimen containing material from more than one layer.

Structural homogeneity of a rock is, unless otherwise stated, considered with respect to specific geometrical features of the body and depends on the number of features considered. A rock homogeneous with respect to one or two specific geometrical features may become heterogeneous when considered in the light of an additional feature. Again the scale of the body under consideration has an important bearing on the degree of homogeneity. A large arbitrarily defined body although statistically heterogeneous as a whole may be subdivisible into smaller units which are statistically structurally homogeneous. However, homogeneity of structure and composition are not necessarily related e.g. a body of folded sedimentary rocks, although structurally homogeneous on the scale under consideration, is quite likely to be compositionally heterogeneous.

Throughout the present discussion homogeneity implies statistical homogeneity unless specifically stated otherwise.

Penetrative Structures (Turner and Weiss, 1963, p. 21).

Structures are regarded as penetrative when they are repeated at distances so small compared with the scale of the whole body that they can be considered to pervade it uniformly and be present at every point. This concept, like that of homogeneity, is dependent on the scale of the investigation. Conversely all other structures are non-penetrative.

Scale (Turner and Weiss, 1963, p. 15).

Microscopic Scale: covering bodies, such as thin sections or polished surfaces, that can be conveniently examined in their entirety with a microscope.

Mesoscopic scale: covers bodies that can be effectively studied in three dimensions by direct observation (with or without a low-power hand lens). They range from hand specimens to large but continuous exposures.

Macroscopic scale: covering bodies too large or too poorly exposed to be examined directly in their entirety. Such bodies are observed indirectly by extrapolation from and synthesis of mesoscopic observations. They range from groups of isolated exposures to the largest mappable bodies.

<u>Tectonic Style</u> (Turner and Weiss, 1963, pp. 78-79).

Tectonic style is an expression which is being used frequently in the literature of structural petrology over the past 10 years but, until recently, never defined. In some respects the term may be regarded as self-explanatory. Its author who is named as Lugeon in Turner and Weiss, 1963, has used it to mean, "the total character of the group of related mesoscopic structures that distinguishes it from a group of comparable structures of another place or age. . .".

<u>Texture</u> (<u>Granoblastic</u>) (Berthelson, 1960, p. 24).

Amoeboid: Neighbouring grains interfere and interlock in a manner suggestive of pseudopodia given off from an amoeba, but the texture - in spite of these irregularities - still has preserved its granoblastic appearance.

Interlobate: When the grain border has a curved or sinuous course, i.e. when the grains are lobate.

Saccharoidal: When the grains border on each other with more or less rectilinear mutual borders.

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FIGURES AND MAPS

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Fig. I-2. View south to Vatersay from the south-east coast of Barra showing low rounded nature of topography.

Fig. I-3. General view of Castlebay and the islands to the south. Vatersay, Sandray, Pabbay, Mingulay and Berneray.

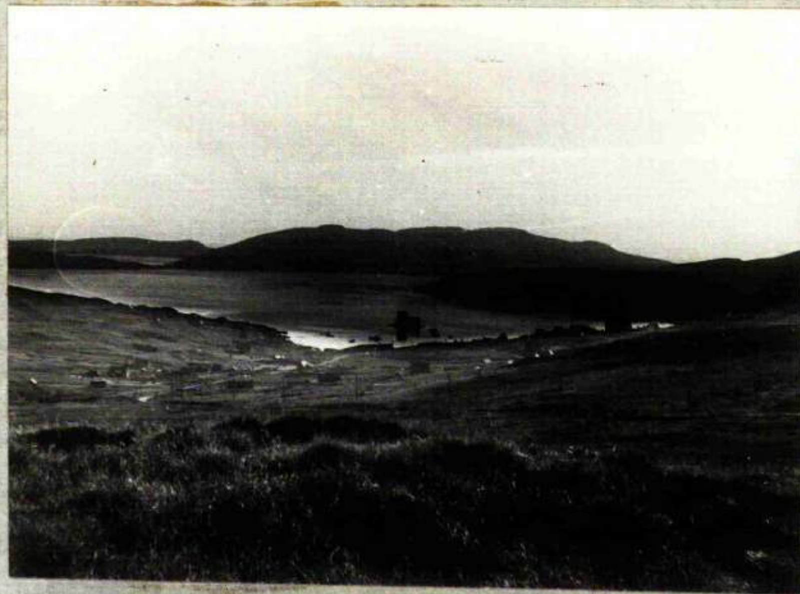


Fig. I-1

Fig. I-2

Fig. I-3

Fig. I-4. Glacial striae (right) on Lewisian dyke which trend 100°. North side of Orosay and Traigh Mhor.

Fig. I-5. Glacial erratic of banded intermediate gneiss perched at 900 feet. In the left background the islands of Fuiary, Flodday, Hellisay and Gighay indicate the line of outcrop of the Thrust. Top of the ridge north of Hartaval.

Fig. I-6. Bedded Quaternary conglomerate on a raised wave cut platform. East end of the beach at Cliad.

Fig. I-4

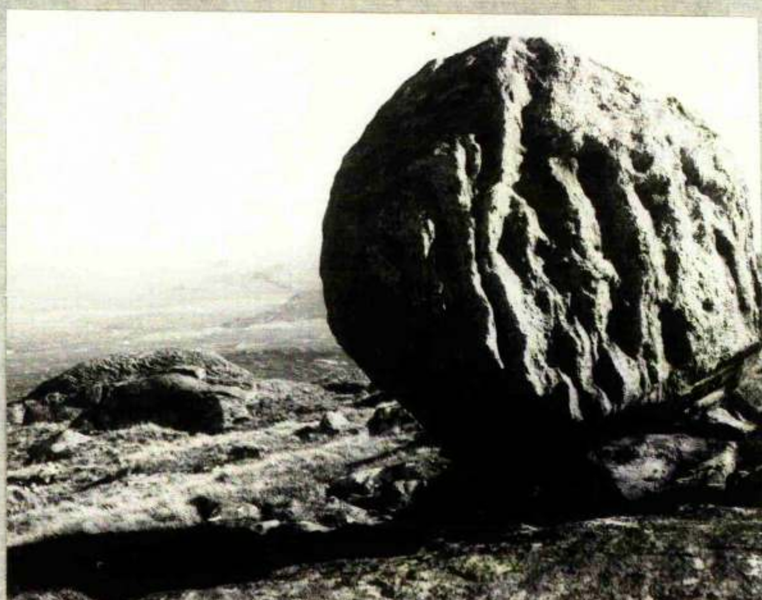


Fig. I-5

Fig. I-6

Fig. II-1. Interference pattern of a complexly folded quartzo-feldspathic vein in amphibolite. North end of Bagh nan Clach.

Fig. II-2. Fold forms in quartz and feldspathic veins in amphibolite resulting from interference by superposed phases of folding. South of Bagh nan Clach.

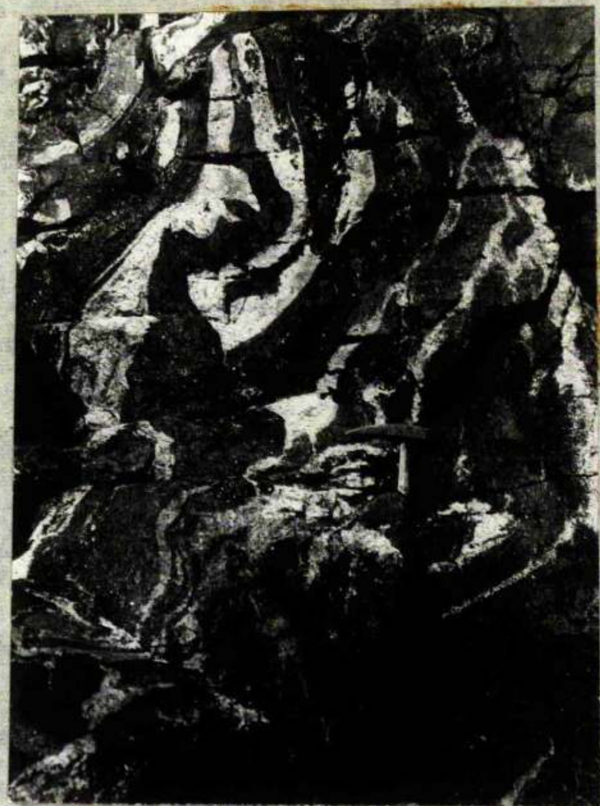


Fig. II-1

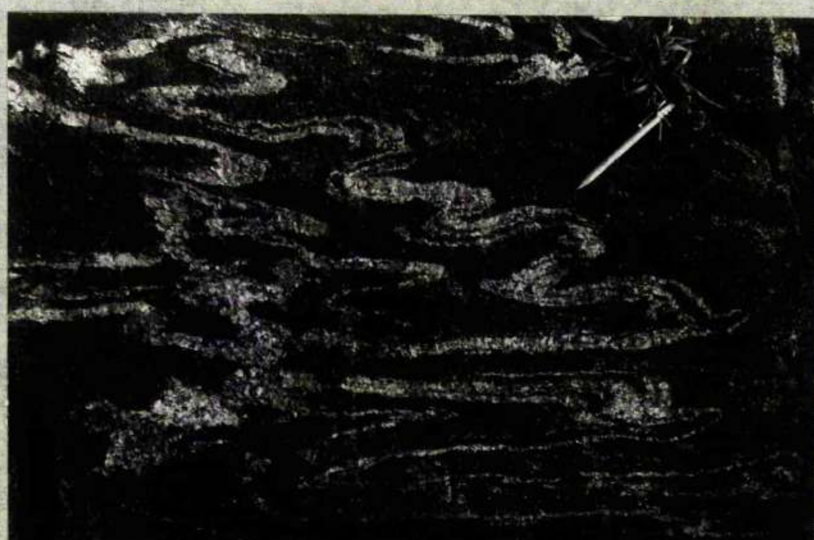


Fig. II-2

Fig. II-3. Section through an isoclinally folded and shear folded quartzo-feldspathic vein in amphibolite at the north end of Bagh nan Clach.

Fig. II-4. Complex fold patterns in amphibolite layers in quartzo-feldspathic gneiss produced by the intersection of a synform refolded about oblique axes. Shore north of Bagh nan Clach.

Fig. II-3

Fig. II-4

Fig. III-1. Flinty crush-breccia cut by rectilinear pseudo-tachylite veins. Shore west of Halaman Bay.

Fig. III-1

Fig. IV-1. Original igneous current bedding preserved in gneiss showing the effects of migmatization to the right of the picture. The floor of the magma chamber lay to the left of the picture. Note intrusive sliver at hammer head. Rudha Mor.

Fig. IV-2. Vesicular weathering amphibolite. Cliff behind the school at Balnacraig.

Fig. IV-1

Fig. IV-2

Fig. V-1. Folds in amphibolite defined by alignment of amphibole and feldspar crystals. The fold closes away from and above to the left of the hammer head. Shore west of Ben Scurrival.

Fig. V-2. Very small folds parallel to the scale which are defined by alignment of mineral grains. Amphibolite, shore north of Bagh nan Clach.

Fig. V-3. Minute folds defined by aggregates of small feldspar crystals. Amphibolite, Rudha Mor.

Fig. V-1

Fig. V-2

Fig. V-3

Fig. V-4. Quartzo-feldspathic vein folded isoclinally. The absence of offshoots or feeders parallel to the foliation indicates that this is not a late vein emplaced parallel to a folded surface. Tangusdale.

Fig. V-5. Isoclinally folded, thin band of amphibolite. Shore, south-west Fiary.

Fig. V-6. Isoclinally folded, interfoliated amphibolite and intermediate quartzo-feldspathic gneisses. South of Bagh nan Clach.

Fig. V-4

Fig. V-5

Fig. V-6

Fig. VI-1. Comparatively late tectonic inclusion (intrafolial fold) of interfoliated basic and intermediate gneiss folded in F_2 style which has been emplaced by shear. West shore of Fiary.

Fig. VI-2. Detached basic shear fold hinges. North of the road between Northbay and Cuier.

Fig. VI-1

Fig. VI-2

Fig. VI-3. Detached hinge of a large mesoscopic amphibolite fold floating in migmatite. A large intrafolial fold. Shore at Scurrival Point.

Fig. VI-4. Small scale refolded, sheared isoclinal quartzo-feldspathic fold. The hinge of the original isoclinal fold is next to the pencil. Borve.

Fig. VI-3

Fig. VI-4

Fig. VII-1. Diagram to show angular and cross cutting relationships between the foliation, Lewisian dykes of Phases 4 and 7 and quartzo-feldspathic pegmatite veins (stippled) outcropping at Leenish.

Fig. VII-2. Diagram to show the effects of dextral shear on dykes (stippled) nearly parallel (a), and nearly perpendicular (b) to the foliation.

Fig. VII-3. Diagram to show the effects of sinistral shear on dykes (stippled) nearly perpendicular (a), and parallel (b) to the foliation.

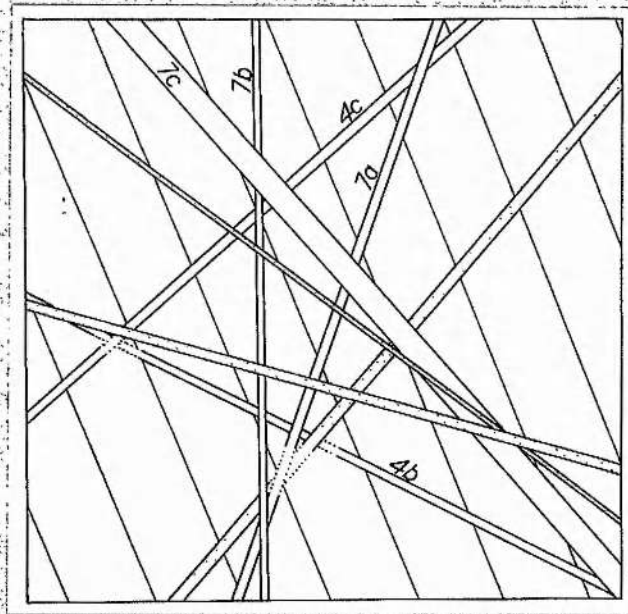


Fig. VII-1

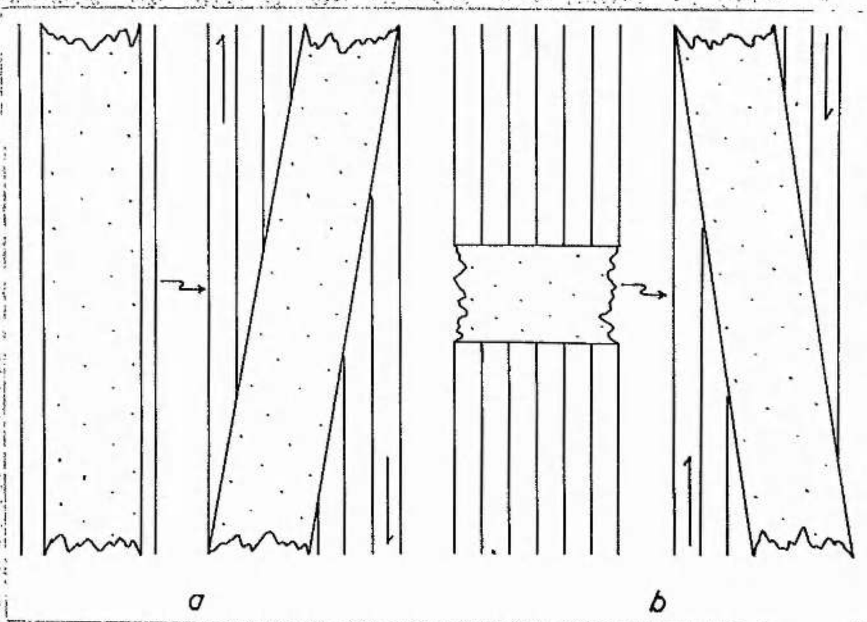


Fig. VII-2

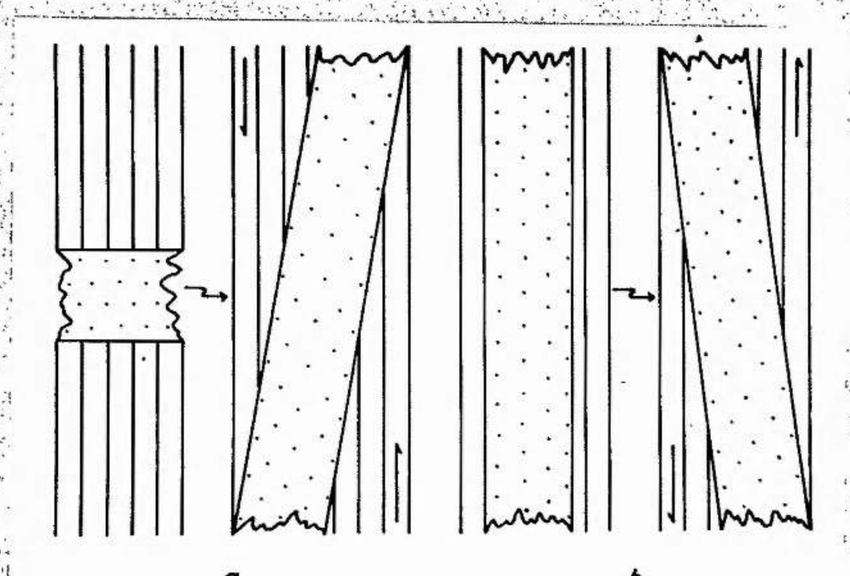


Fig. VII-3

Fig. VII-4. Diagram to show the effect of shear reorientation of lines inclined at different angles to the direction of shear. Ratio of shear movement to separation between shear surfaces in each case is $\frac{1}{3}$ spacing between shear surfaces. To bring a line inclined at 90° to the shear direction to within 5° of the shear direction the slip on the shear surfaces must exceed 10 times their separation.

Fig. VII-5. Showing angles of inclination of dyke to foliation at which foliation shear could effectively alter the orientation. The number of possible directions ranges from a maximum when the shear (foliation) surface (hatched) is perpendicular to the dyke, to one when the shear surface is tangential to the surface of the cone.

Fig. VII-6. Mechanism of foliation shear reorientation in dykes. The angle α remains constant and therefore the dyke (stippled) can never become parallel to the foliation (shear) surfaces. XY is the intersection between the dyke and the foliation. α is the angle between XY and the shear direction. β is the angular difference between the strike of the dyke and that of the foliation before shearing (a) γ the angle after shearing (b).

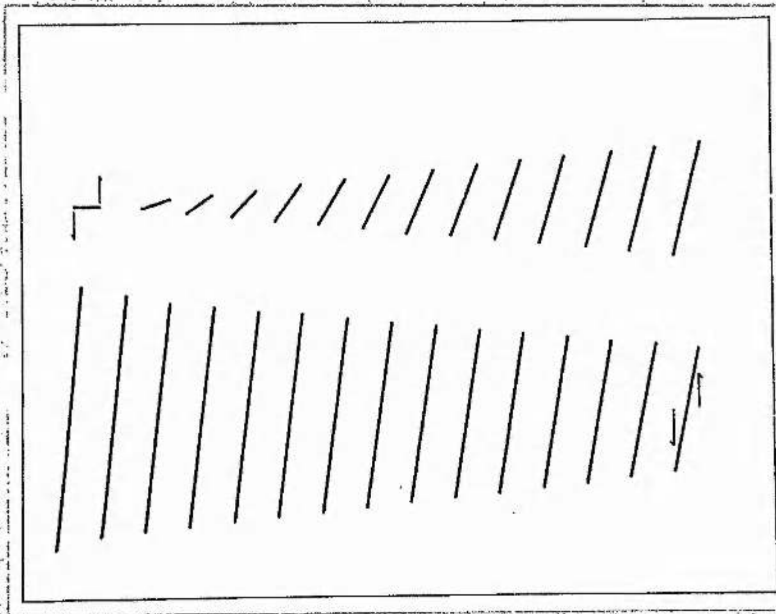


Fig. VII-4

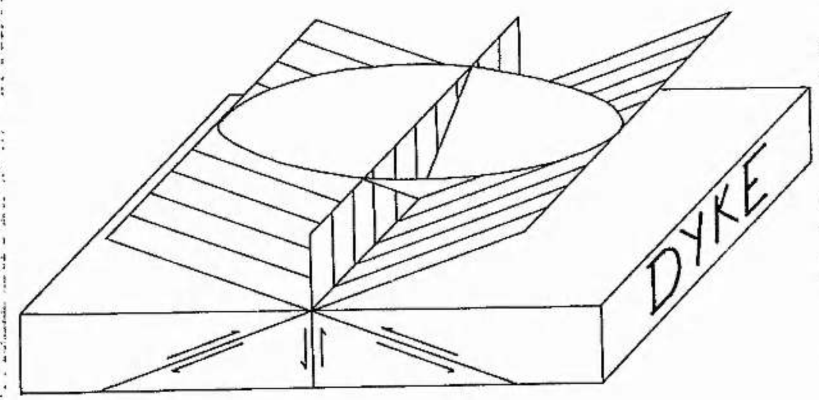


Fig. VII-5

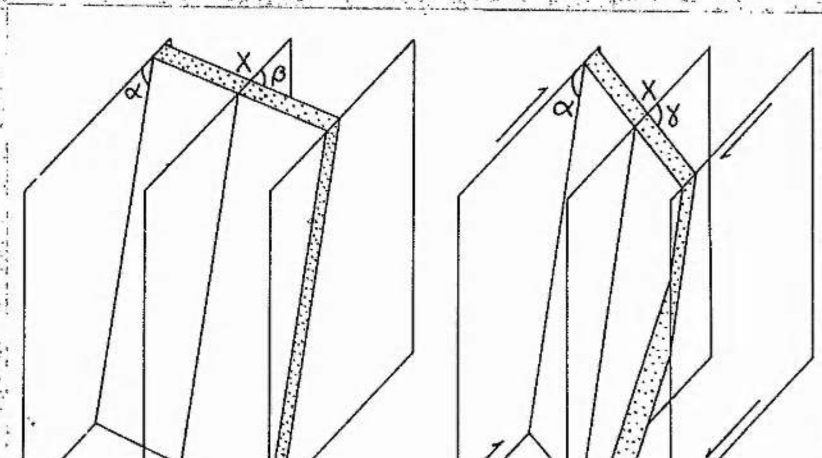


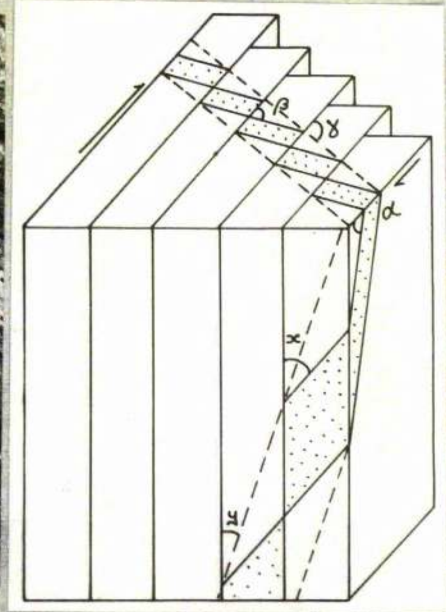
Fig. VII-6

Fig. VII-7. a. Sheared quartzo-feldspathic vein providing an example of the effect of shear shown in b.
b. Shearing of dyke (stippled) in segments parallel to the foliation by foliation shear. The angles γ and y are the new angles between the dykes (i.e. its enveloping surface) and the foliation.

Fig. VII-8. Dyke reorientation about an axis oblique to the direction of shear. Shear between the dyke and the foliation (single barbed arrows) is parallel to the axis of rotation and oblique to the direction of foliation shear (double barbed arrows).

Fig. VII-9. Resultant shear of "parallel" and oblique mechanisms.
a. Position of the dyke before shear. b. Position of the dyke after shear. c. Plan of shear reoriented dyke.

a.



b.

Fig. VII-7

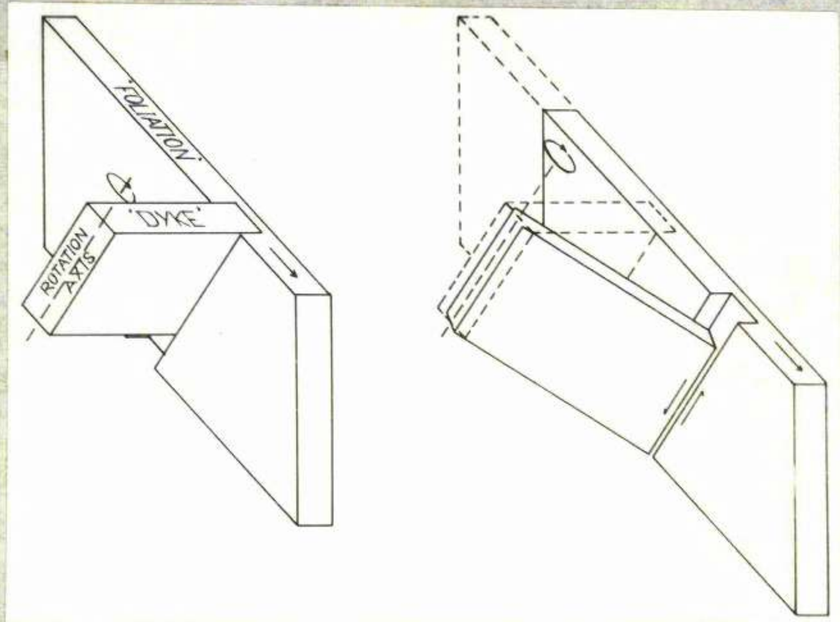


Fig. VII-8

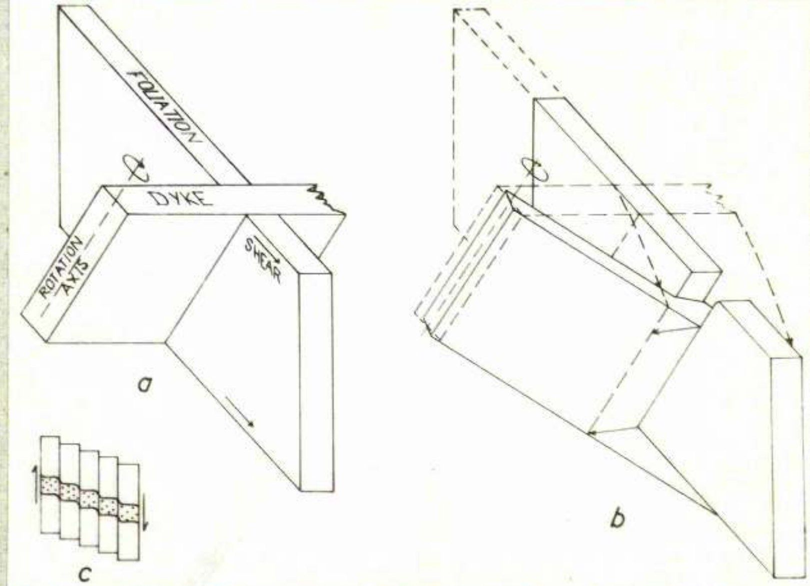


Fig. VII-9

Fig. VII-10. Effect of outcrop attitude on apparent angular relationship between dyke (stippled) and foliation.

Fig. VII-11. Thin feldspathic vein in a Lewisian dyke apparently folded by shear parallel to the dyke margins. Hillside north of Alt Heiker.

Fig. VII-12. Lewisian dyke (striking away from camera) cutting through a wide pegmatite vein at hammer and itself cut by a narrow, rectilinear, 140° trending pegmatite vein in the background. Note the xenoliths at the dyke margin in front of the hammer. Orosay, Traigh Mhor.

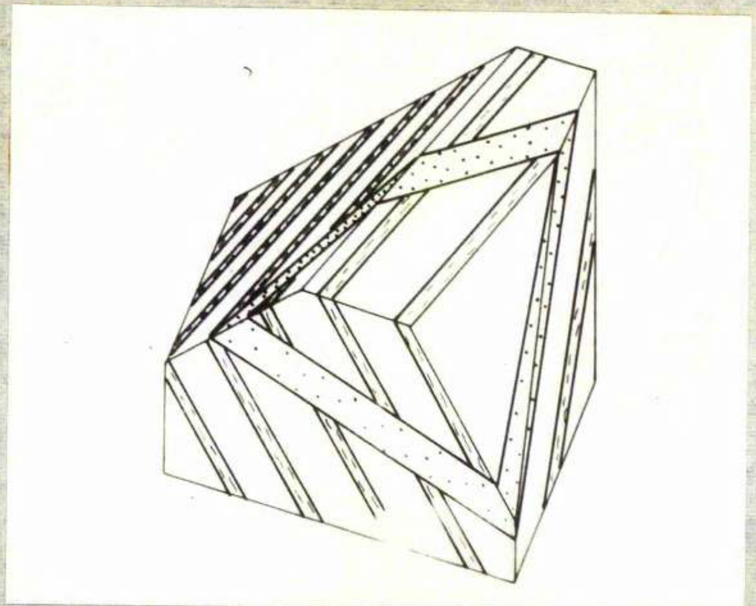


Fig. VII-10

Fig. VII-11

Fig. VII-12

Fig. VII-13. Lewisian dyke dipping towards the sea (under hammer) cutting an earlier dyke which dips to the left and strikes out to sea. (See map IX). Leenish.

Fig. VII-14. Late Lewisian dykes (grey rectilinear near camera and to the left) cutting foliated gneiss. The earlier dark dyke to the right of the left hand grey dyke still retains traces of its original elongate form but the other, even earlier intrusives are now represented only by detached fold hinges (centre) and lenses (right and at hammer). Shore south of Brevig Bay.

Fig. VII-15. A Lewisian dyke cutting an earlier thin basic dyke (left of hammer) and a pegmatite vein striking diagonally away to the left. The earlier dyke remnant is oblique to the foliation. Shore at Leenish.

Fig. VII-13

Fig. VII-14

Fig. VII-15

Fig. VII-16. Coarse mottled green pyroxene (grey) and hornblende (black) early intrusive of Phase 4a. Shore at Leonish.

Fig. VII-17. Coarse epidiorite of Phase 4a. The marginal phase of a very coarse hornblende rich ultrabasic Lewisian dyke showing relict ophitic texture. North of Ben Gunnary.

Fig. VII-18. Photomicrograph of an intrusive of Phase 4a (Specimen 725). Plane polarized light. x 15. Pyroxene porphyroblasts at top right and lower left nested in flakes of biotite.

Fig. VII-16

Fig. VII-17

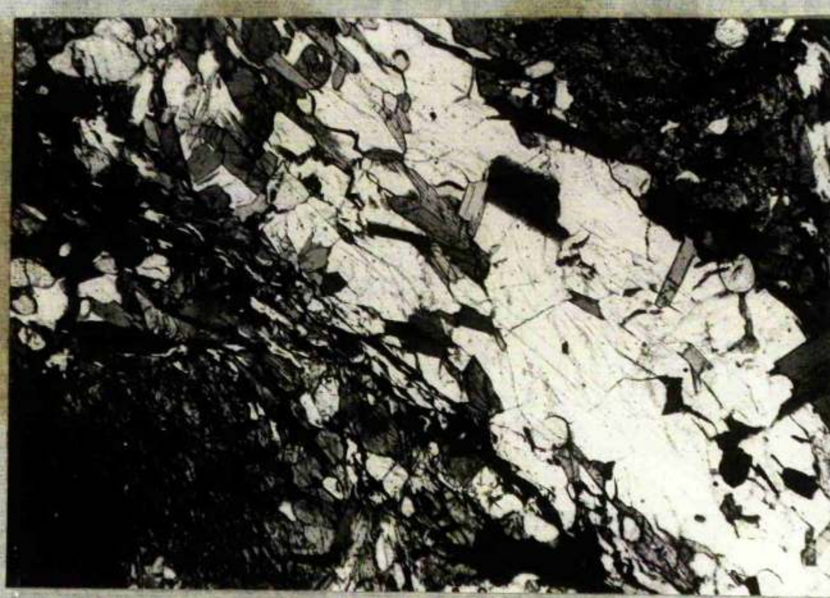


Fig. VII-18

Fig. VII-19. Four inch wide green hornblende and pyroxene dyke dipping west and cutting banded migmatite (parallel to hammer handle). Shore south of the entrance to Loch Obe.

Fig. VII-20. Photomicrograph of an intrusive of Phase 4b (Specimen 737). Plane polarized light. x 15. Bladed biotite, hornblende, andesine and few granules of clinopyroxene.

Fig. VII-21. Garnetiferous basic hornblende knots (above hammer and in foreground) in banded basic and intermediate gneiss. North end of Bagh nan Clach.

Fig. VII-19

Fig. VII-20

Fig. VII-21

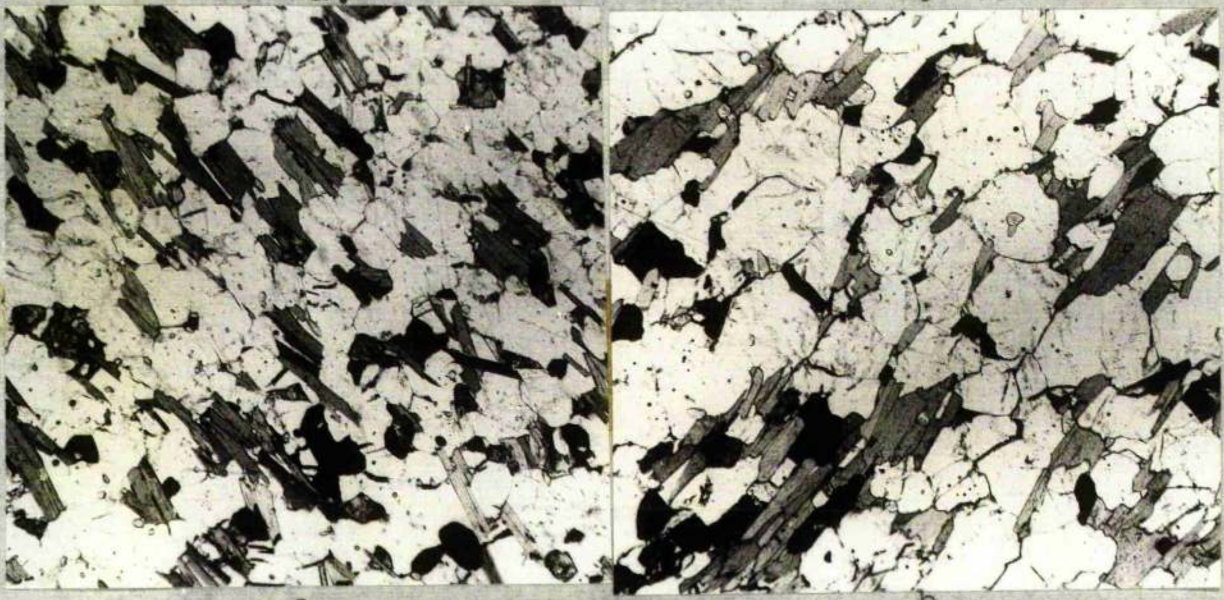
Fig. VII-22. Photomicrograph of a coarse grained intrusive of Phase 4b. a. (Specimen 684). b. (Specimen 475). Plane polarized light. x 15. Flakes of biotite in b (grey), hypersthene, olivine in a (fractured) and magnetite.

Fig. VII-23. Photomicrograph of an intrusive of Phase 4c. a. (Specimen 731) fine. b. (Specimen 749) coarse. Plane polarized light. x 15. Andesine, biotite, magnetite and apatite.

Fig. VII-24. Folded amphibolite intrusives in migmatite. Small xenoliths of country rock can be seen in the arch of the fold nearest the camera. Shore north of Ru fear Vatersay.

a. b.

Fig. VII-22



a. b.

Fig. VII-23

Fig. VII-24

Fig. VIII-1. Cyclographic plot of an F_2 fold to show the direction of plunge on a north dipping limb of an F_1 fold reorientated from its position on the east dipping limb. On the east dipping limb F_1 plunges at 54° towards 30° and on the north dipping limb F_1 plunges at 28° towards 310°.

Fig. VIII-2. Equal area plot of attitudes of F_1 small fold axes relative to the foliation. West end of Halaman Bay.

Fig. VII-3. Remnants of north-east plunging small folds and north-east trending irregular quartzo-feldspathic pegmatite veins axial planar to the folds. West of road at Brevig.

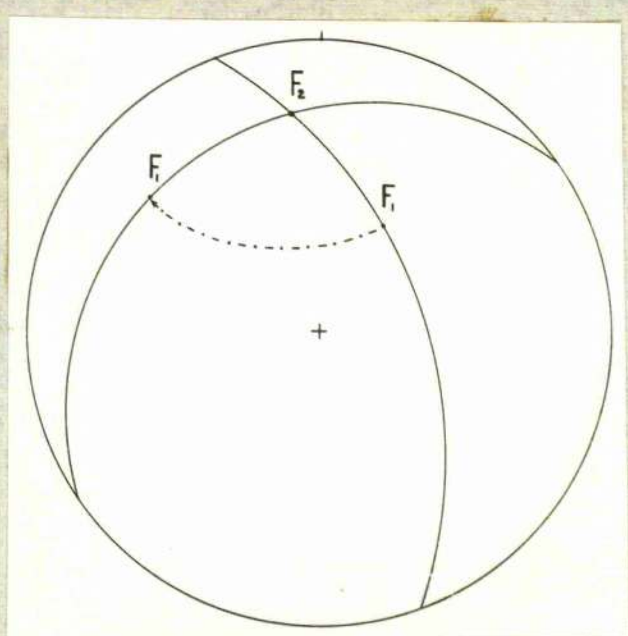


Fig. VIII-1

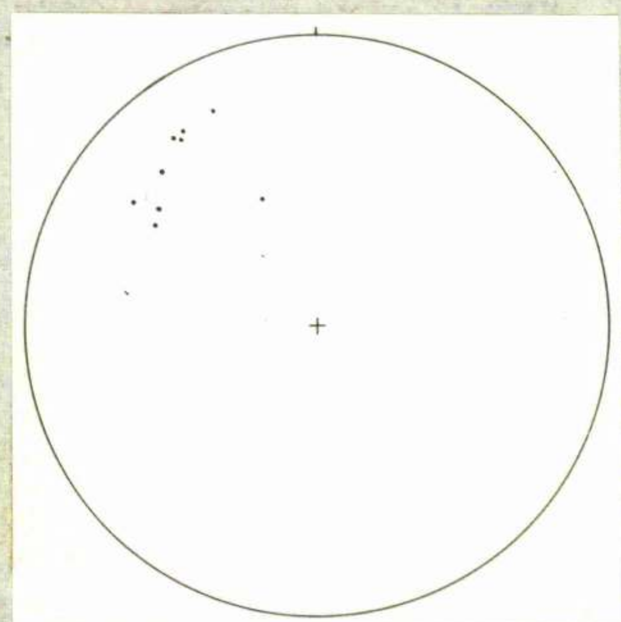


Fig. VIII-2

Fig. VIII-3

Fig. VIII-4. Diagram of the crosscutting relationships between two Lewisian dykes, and 60° and 30° trending quartzo-feldspathic pegmatite veins (stippled). Leenish.

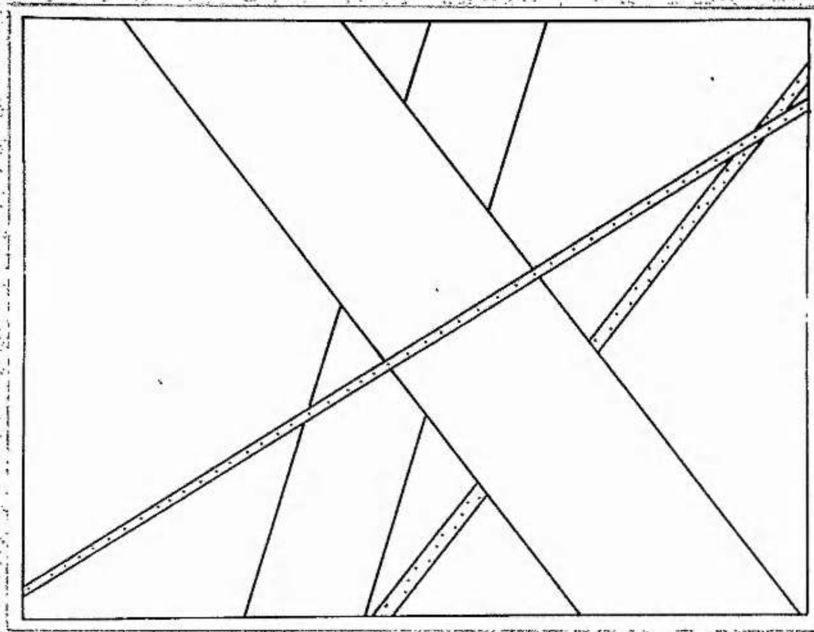


Fig. VIII-4

Fig. IX-1. Boudinaged Lewisian dyke. North side of Orosay, Traigh Mhor.

Fig. IX-2. Rotated basic boudins in intermediate gneiss which has reached an advanced state of anatexis. Note darkened rim adjacent to migmatite at hammer and detached shells floating off into migmatite.

Fig. IX-3. Strongly migmatized rotated skeletal boudins in banded migmatite. Shore north of Bagh nan Clach.

Fig. IX-1

Fig. IX-2

Fig. IX-3

Fig. IX-4. Boudins in banded migmatite which have been affected by F_4 folding. The boudins show signs of having been compressed laterally, squeezed against one another and rotated slightly. West coast south of Doirlinn.

Fig. IX-5. Large basic boudins in migmatite. Note the evidence of flow of quartzo-feldspathic material to the left from the separation between the boudins at the hammer and obliteration of the foliation by the migma flow. West of Ben Scurrival.

Fig. IX-6. Small basic boudins. West coast south of Ard na Gregaid.

Fig. IX-4

Fig. IX-5

Fig. IX-6

Fig. IX-7. Development of small boudins on the flank of a small F_2 fold. Bagh nan Clach.

Fig. IX-8. Diagram to show the orientations of maximum stress in relation to boudins in different parts of the field. a. Ard na Gregaid. b. Doirlinn Head. c. Scurrival. d. Bagh nan Clach.

Fig. IX-9. Strongly migmatised gneiss containing relict banding outlined by elongate basic enclaves. West coast of Fiary.

Fig. IX-7

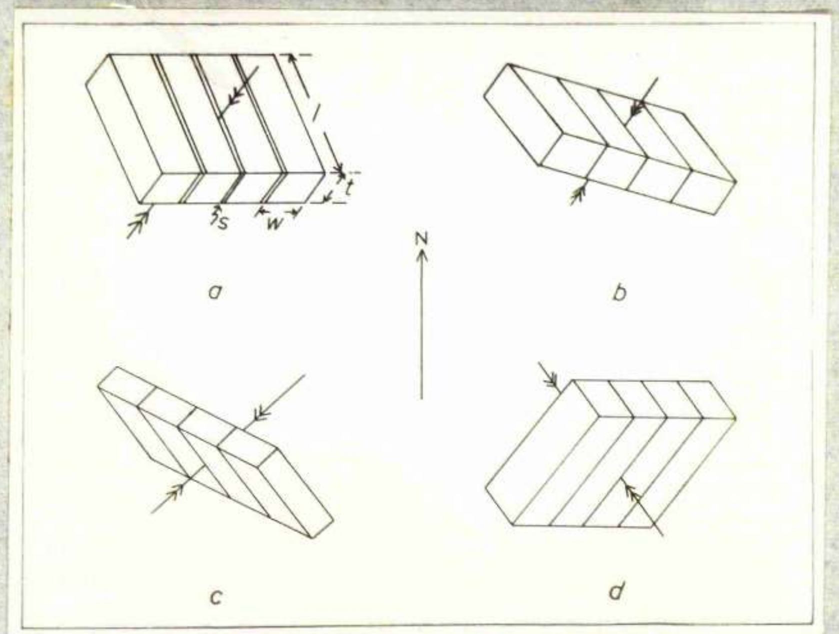


Fig. IX-8

Fig. IX-9

Fig. IX-10. Agmatite comprising small fold hinges and basic boudins in migmatite. West coast of Fiary.

Fig. IX-11. Replacement agmatite surrounded by quartzo-feldspathic segrations. South shore at Rudha Mor.

Fig. IX-12. Hornblende pyroxene balls rimmed with biotite in coarse pink feldspathic, homogeneous gneiss. Leenish.

Fig. IX-10

Fig. IX-11

Fig. IX-12

Fig. IX-13. Coarse hornblende pegmatite associated with pink feldspathic pegmatite. South coast of Bruernish.

Fig. IX-13.

Fig. X-1. Photomicrograph of an intrusive of Phase 7a (Specimen 735) showing lepidoblastic texture. x 15. Plane polarized light. Andesine, bladed biotite (grey), apatite granules and some small dark grains of hornblende.

Fig. X-2. Photomicrograph of a Phase 7b (Specimen 729) intrusive showing nematoblastic texture. x 15. Plane polarized light. Andesine, bladed biotite (grey), dark hornblende and apatite granules.

Fig. X-3. Photomicrograph of a Phase 7c (Specimen 744) intrusive showing granoblastic texture. x 15. Plane polarized light. Andesine, hornblende and clinopyroxene.

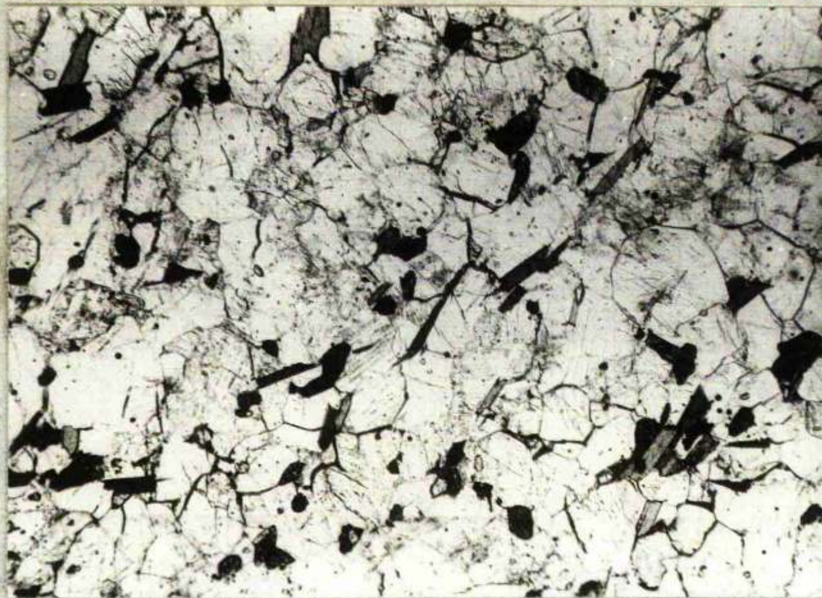


Fig. X-1

Fig. X-2

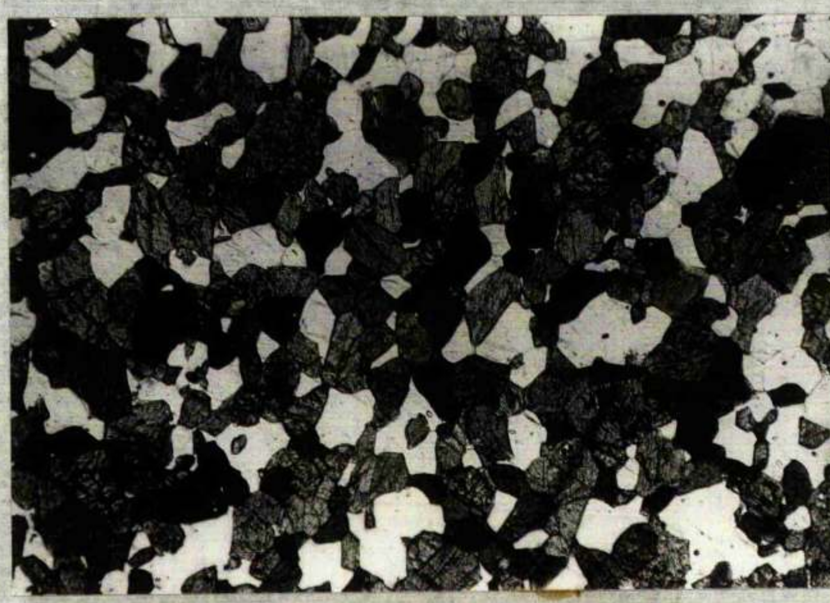


Fig. X-3

Fig. X-4. Hornblende granulite dyke. Eight inches wide (cf. fig. VII-15). South shore of Brevig Bay.

Fig. X-5. Hornblende-pyroxene granulite dyke 50 yards wide cut by 6 inch quartzo-feldspathic pegmatite vein from which branch thin veinlets with curved junctions. Note the darkening of the dyke adjacent to the thin vein on the left of the photograph. (cf. fig. XIX-2). Leenish.

Fig. X-6. Hornblende granulite dyke. Two inches wide. North-west corner of Brevig Bay.

Fig. X-4

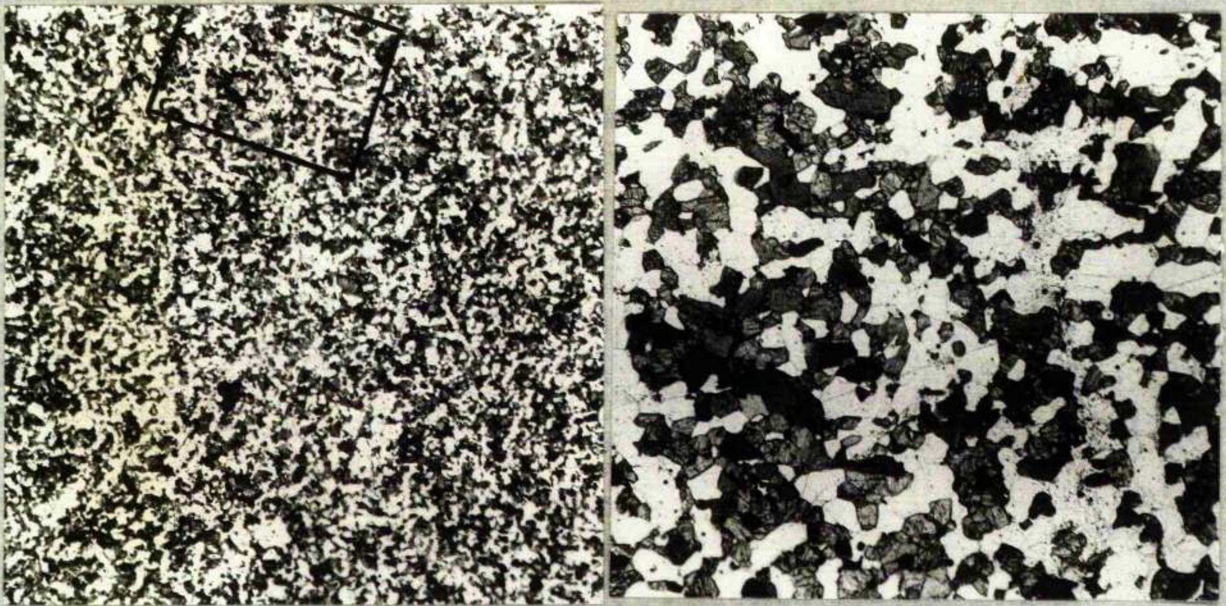
Fig. X-5

Fig. X-6

Fig. X-7. Photomicrograph of a Lewisian dyke of Phase 7c (Specimen 613) showing relict ophitic texture. Plane polarized light. a. x 4. Area of b enclosed by rectangle. b. x 15. Andesine, hypersthene (grey) and magnetite.

Fig. X-8. Photomicrograph of the same granulite dyke as figure X-7 showing granular texture reslting from complete metamorphic recrystallizaion. x 15. Crossed nicols.

Fig. X-9. Photomicrograph of a pyroxene granulit of Phase 7c (Specimen 733). x 15. Plane polarize light. Andesine, hypersthene (grey) and magnite.



a. b.

Fig. X-7

Fig. X-8

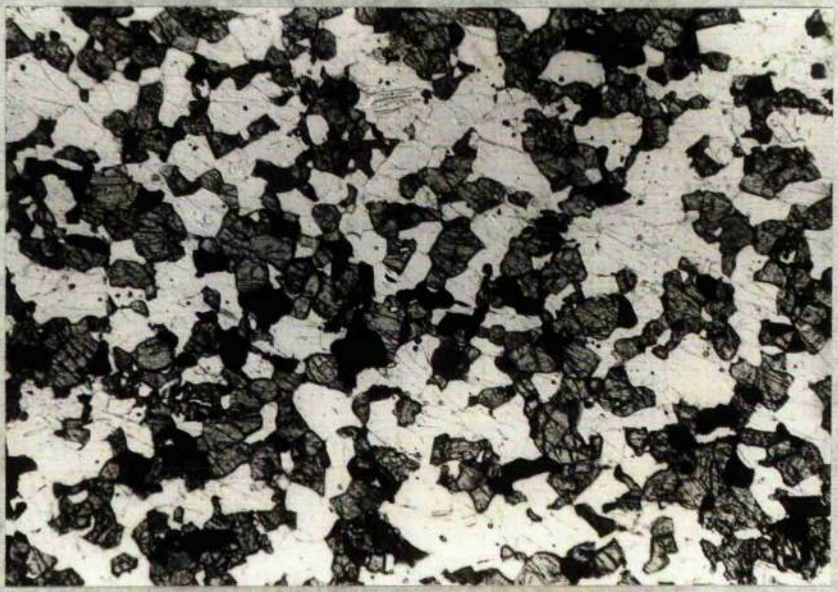


Fig. X-9

Fig. X-10. Photomicrograph of the contact (Specimen 665) between a Phase 7c basic dyke and acid pyroxene granulite facies country rock (Specimen 668). x 15. Plane polarized light. Andesine, hypersthene (grey) and a few grains of hornblende (dark grey) can be seen in the dyke on the right of the figure.

Fig. X-11. Photomicrograph of pyroxene granulite from Skallary (Specimen 627). x 15. Plane polarized light. Andesine, hypersthene (grey), garnet (fractured) and a little magnetite (black).

Fig. X-12. Photomicrograph of amphibolite (Specimen 549). x 15. Plane polarized light. Andesine, hornblende (dark grey) and a few grains of clinopyroxene (equant grains).

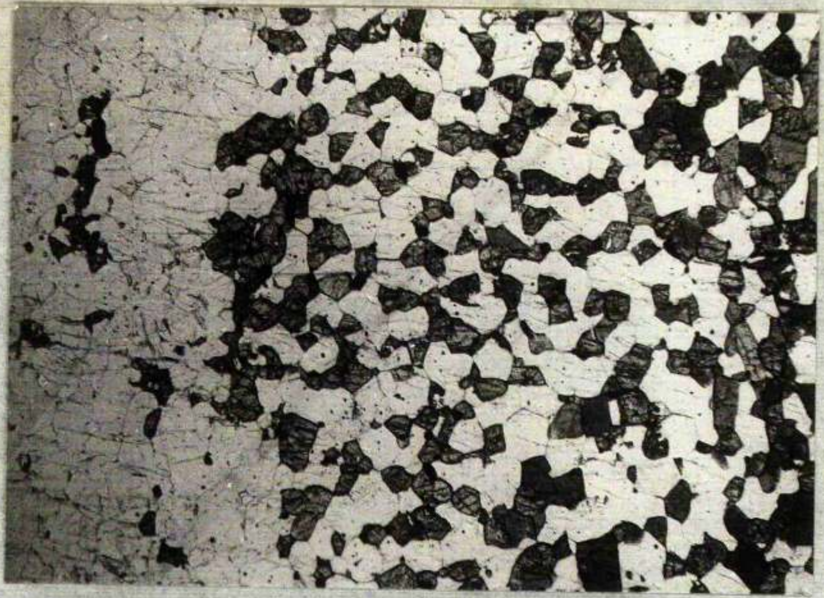


Fig. X-10

Fig. X-11

Fig. X-12

Fig. XI-1. Map showing the distribution of specimens of gneisses of different metamorphic facies. Pyroxene granulites solid circles; hornblende granulites open circles with dots; amphibolites open circles.

Fig. XI-2. Sketch map of the south end of the Rudha Liath dyke showing the location of specimens collected. Pyroxene granulite, solid circles. Hornblende granulite, circles with dots; almandine amphibolite, open circles; almandine amphibolite to greenschist, small circle.

Fig. XI-3. Block diagram of the Rudha Liath dyke cut by pegmatite veins (black) to show postulated directions of movement of the migmatite front and the effect on this movement of the impermeability of the dyke.

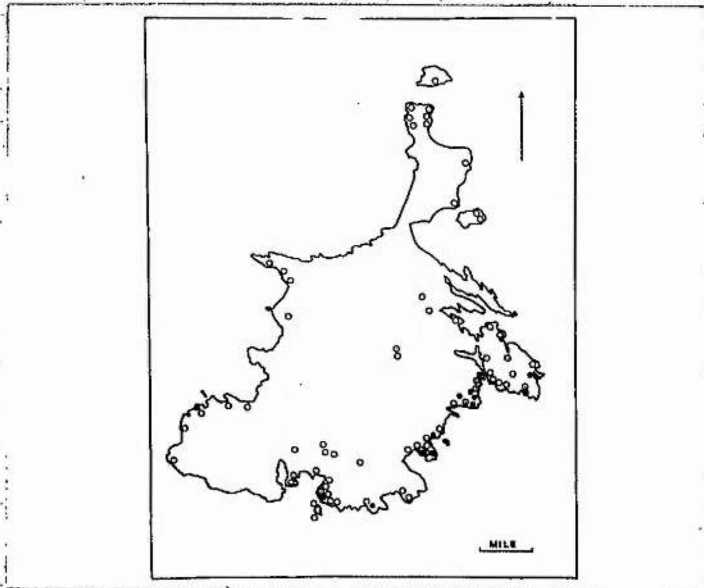


Fig. XI-1

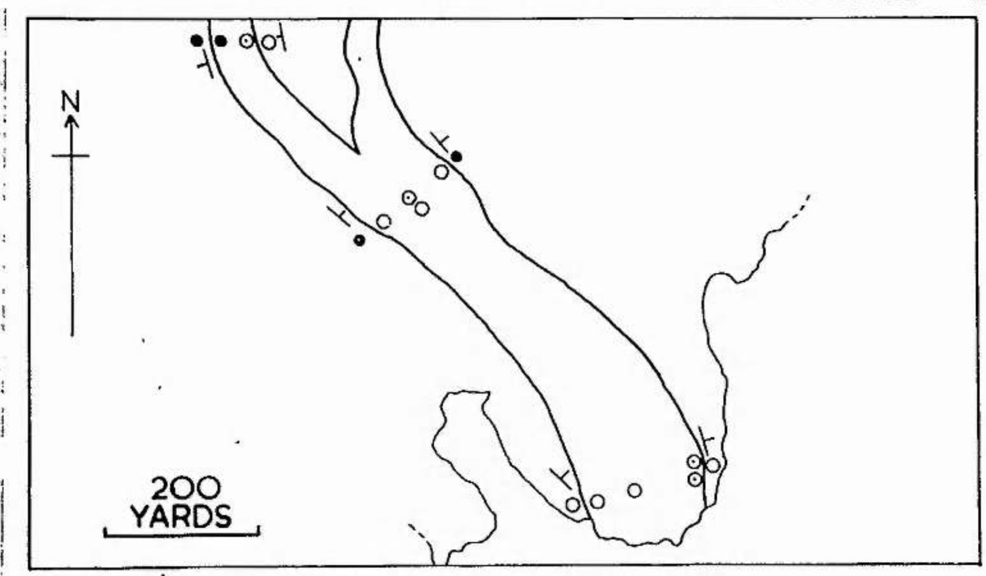


Fig. XI-2

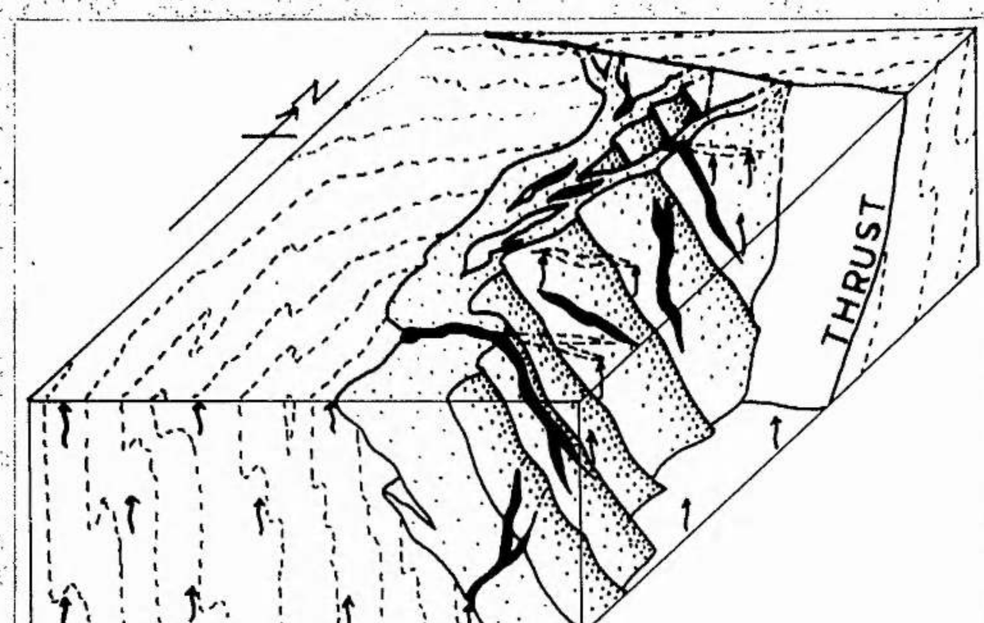


Fig. XI-3

Fig. XII-1. View looking north-east of a mesoscopic F_2 fold showing the gently north dipping north limb, the overturn at the hinge to the steeply east dipping west limb and the start of the north dipping south limb (breached by pegmatite at the small fault). North-west side of Scurrival Peninsular.

Fig. XII-2. Horizontal section through a mesoscopic F_2 fold looking west to show the 120° striking axial plane. Shore at Orosay, Traigh Mhor.

Fig. XII-3. Large mesoscopic F_2 fold looking north-east oblique to axial plunge. Shore at Ard na Gregaid.

Fig. XII-1

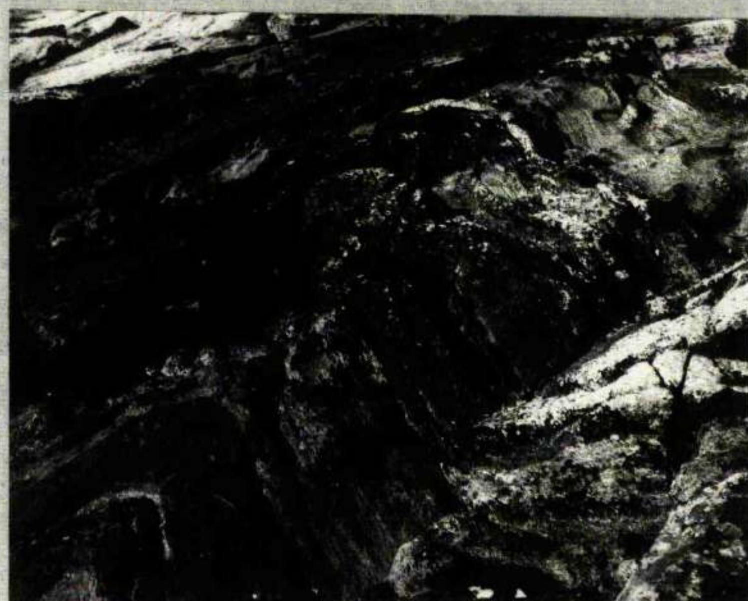


Fig. XII-2

Fig. XII-3

Fig. XII-4. Curvature from 100° (nearest the camera) to 140° of axial planar trend in an F_2 fold warped about an F_5 axis. Shore at the west end of Halaman Bay.

Fig. XII-5. Antiform of buff coloured (centre of photograph) ? paragneiss closing to the north just beyond sloc at the hinge of narrow quartzo-feldspathic fold in centre background. North of Bagh nan Clach.

Fig. XII-6. Cyclographic plot in equal area projection of arithmetically averaged attitudes of north and west limbs of the macroscopic Scurrival F_2 fold.

Fig. XII-4

Fig. XII-5

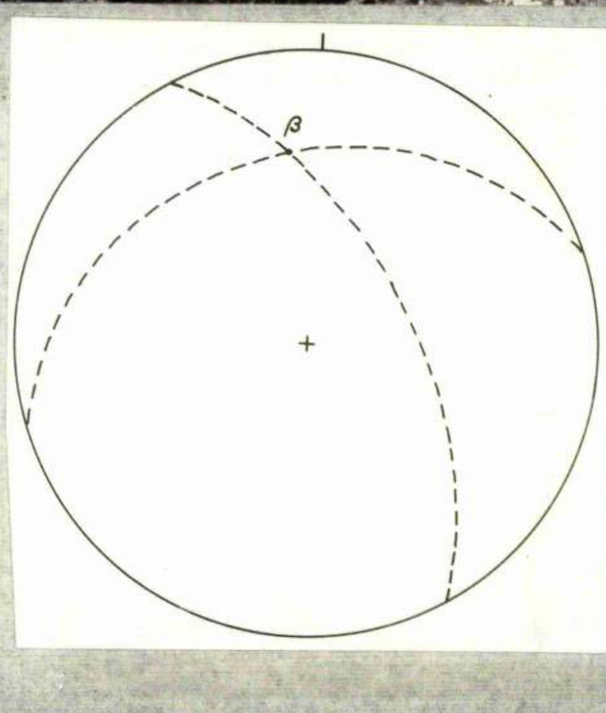


Fig. XII-6

Fig. XII-7. Equal area plot of poles to foliation from the north limb of the Scurrival F_2 fold. Contours at 2.5%, 5%, 10%, 15% and 20% intervals.

Fig. XII-8. Equal area plot of poles to foliation from the west limb of the Scurrival F_2 fold. Contours at 1%, 2%, 4%, 6% and 8% intervals.

Fig. XII-9. Equal area plot of poles to foliation from the south limb of the Scurrival F_2 fold. Contours at 5%, 10%, 20% and 20% intervals.

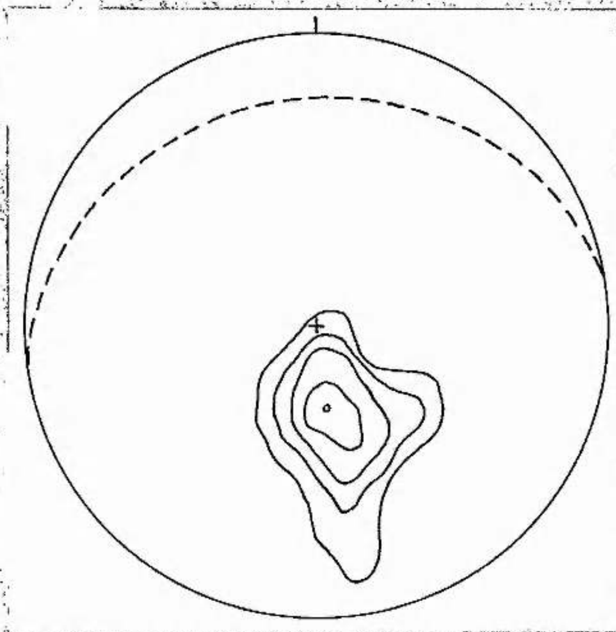


Fig. XII-7

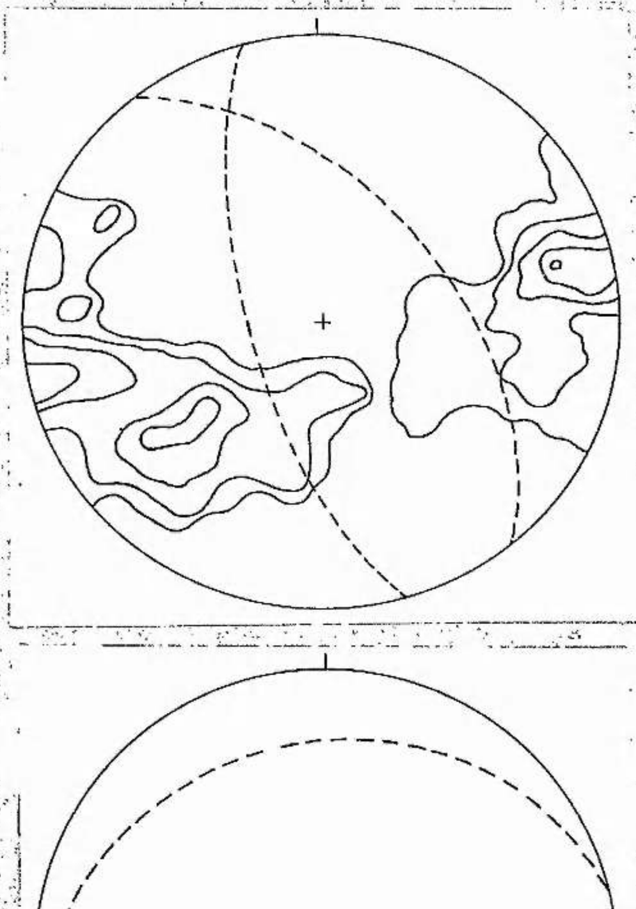


Fig. XII-8

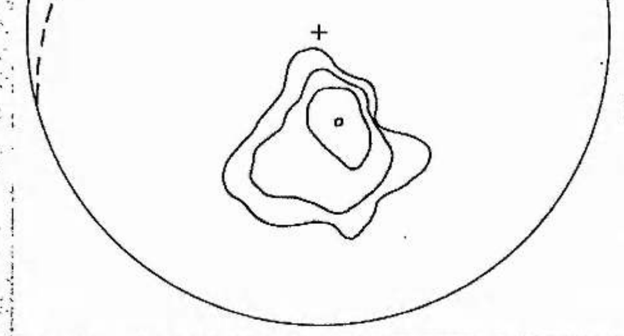


Fig. XII-9

Fig. XII-10. β-diagram of fold limbs whose attitudes have been determined from maxima of plots of poles to foliation on the north, west and south limbs of the Scurrival F_2 structure, and the west dipping part of the west limb close to the south limb. β plunges at 20° towards 340°.

Fig. XII-11. π S-poles girdle of all poles to foliation of the Scurrival F_2 fold defining the fold axis F_2 plunging at 25° to 345°. Contours at 1%, 2.5%, 5%, 7.5% and 10% intervals.

Fig. XII-12. Equal area plot of axial trends (and axial planar trends) of small folds on the limbs of the Scurrival F_2 fold. Contours at 2.5%, 5%, 10% and 15% intervals.

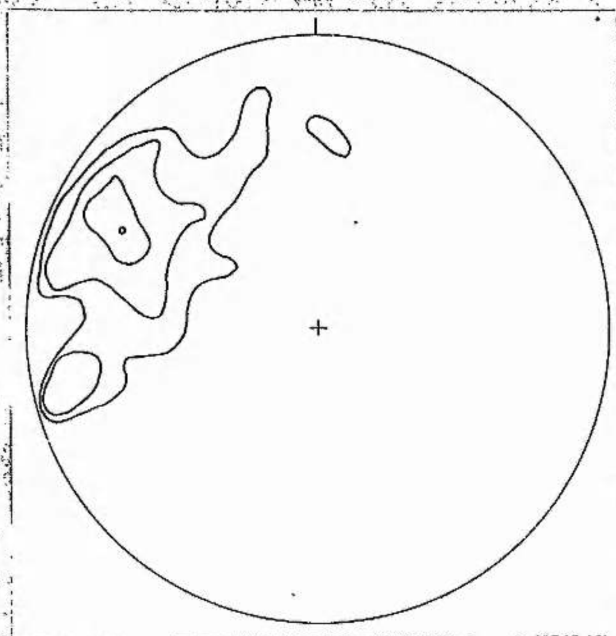


Fig. XII-10

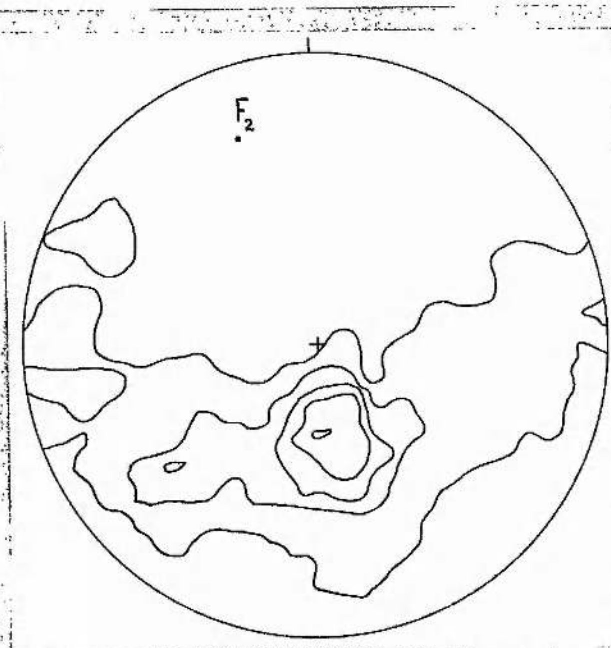


Fig. XII-11

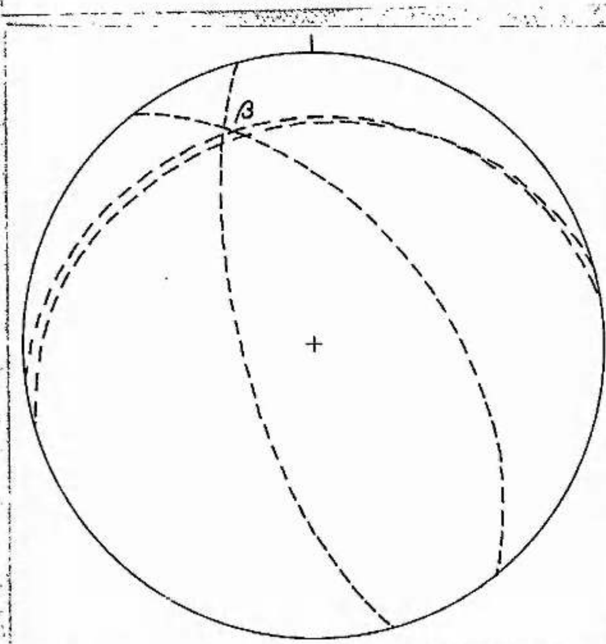


Fig. XII-12

Fig. XII-13. Faulted folds of F_2 style showing asymmetry of form and incipient migmatization parallel to the axial crests. West of the road above Brevig.

Fig. XII-14. Transverse profile of Scurrival F_2 fold looking down plunge. Constructed from map II.

Fig. XII-15. Small scale F_2 "step folds" probably accentuated by shear. Shore at Ard Mhor.

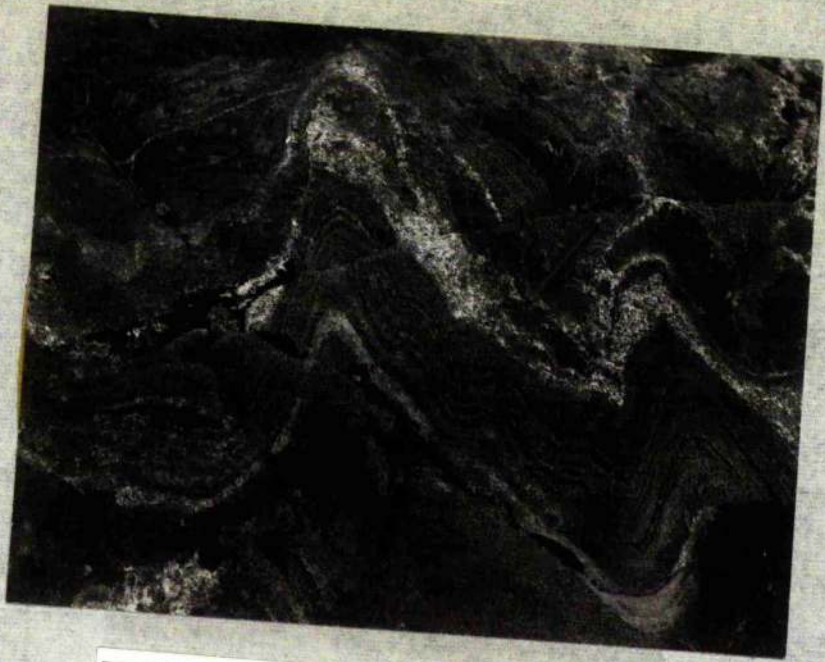


Fig. XII-13

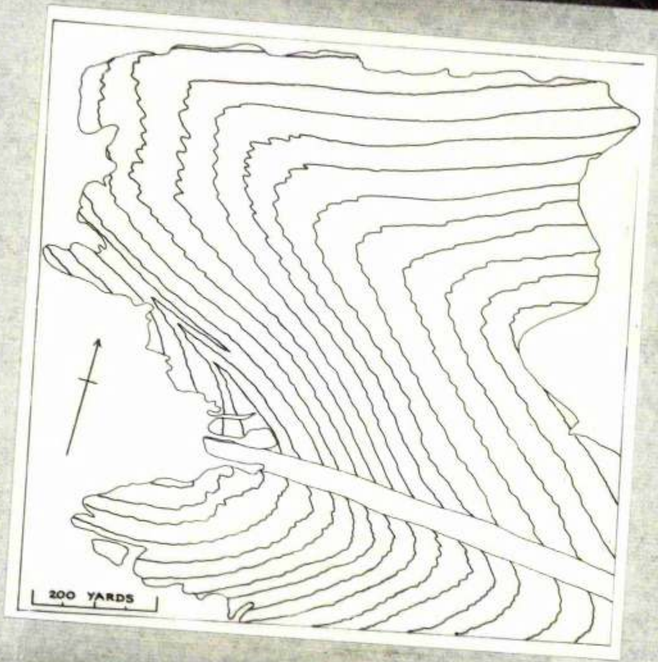


Fig. XII-14

Fig. XII-15

Fig. XII-16. Equal area plot to show 118^{o} strike of the axial surface of the Scurrival F_2 fold plotted on the assumption that this is symmetrically disposed to the east dipping west and north limbs.

Fig. XII-17. Equal area plot of the strikes of the axial surfaces of 77 small folds at Scurrival. This shows the 116^{o} trend of the F_2 fold determined statistically from folds whose attitudes have been measured in the field. Contours at 2½%, 5%, 10% and 15%. The secondary maximum is due to the combined effects of F_4 and F_5 folds.

Fig. XII-18. A mesoscopic F_2 "step fold". West coast of Fiary.

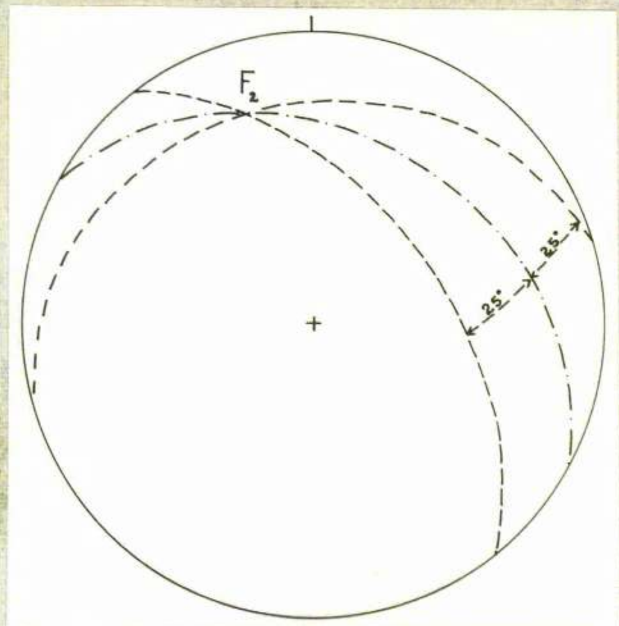


Fig. XII-16

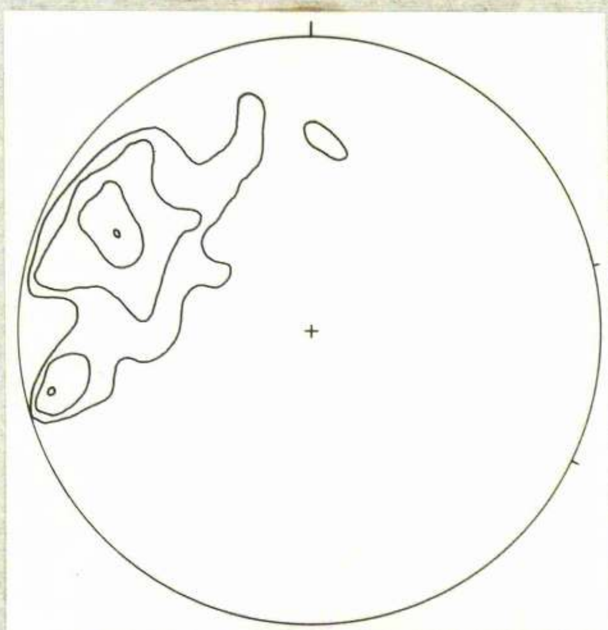


Fig. XII-17

Fig. XII-18

Fig. XII-19. Diagram to show the angular relationship between the axial planar surface and the enveloping surface of the Scurrival fold, showing its monoclinic symmetry. (Compare figure XII-13).

Fig. XII-20. Diagram to show a hypothetical form of a plot of poles to foliation of the Scurrival style of fold.

Fig. XII-21. Profile of a small F_2 fold. Hillside above the School, Eoligarry.

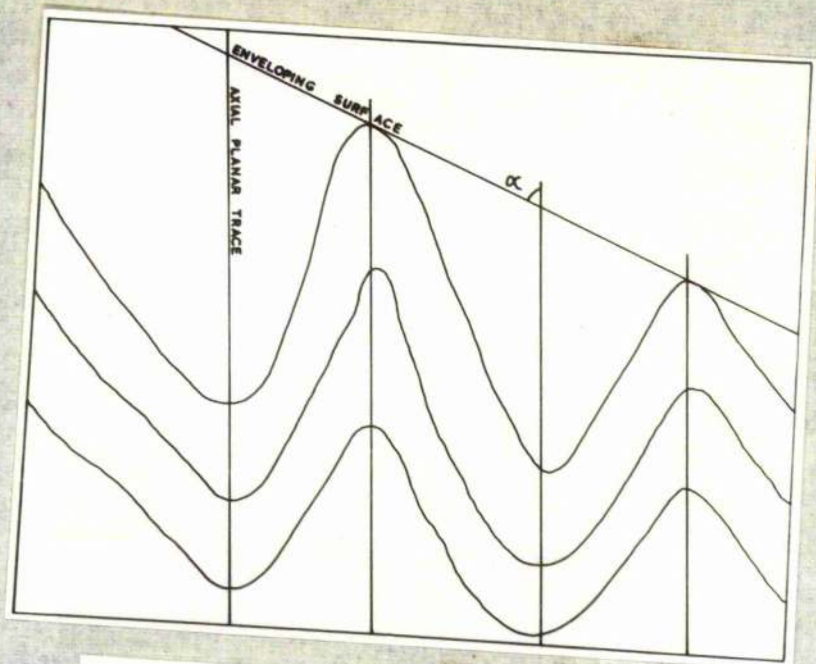


Fig. XII-19

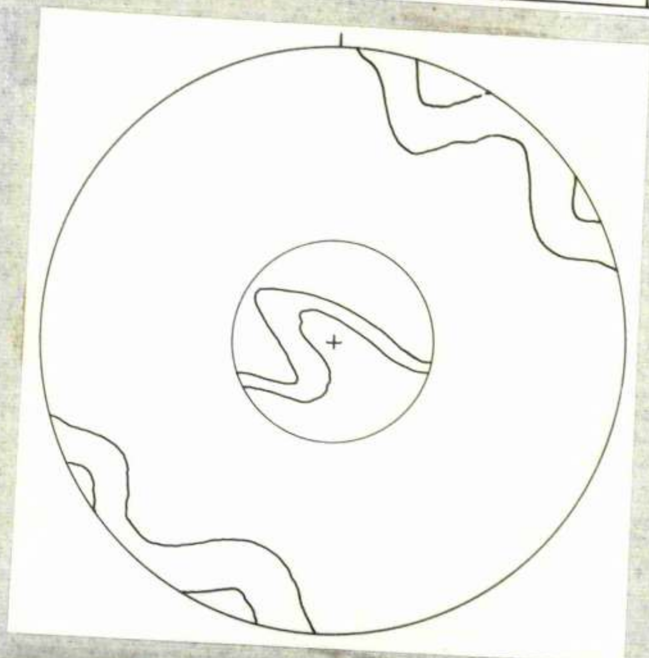


Fig. XII-20

Fig. XII-21

Fig. XII-22. The F_2 fold of figure XII-2 looking north-east. Orosay.

Fig. XII-23. Vertical section through an F_2 style of fold. View looking 40°. Orosay Traigh Mhor.

Fig. XII-24. View looking 330° of the same fold as figure 23. The hammer is in the same position in each photograph. Note the different appearance of this structure when viewed in different section.

Fig. XII-22

Fig. XII-23

Fig. XII-24

Fig. XII-25. View looking towards 300° along the axial planar trend of F_2 style of folding. Hillside north of the School, Eoligarry.

Fig. XII-26. Small folds of F_2 style showing asymmetrical nature and trend of axial crests parallel to 120°. The small fold in the centre foreground shows the gently dipping north limb and the overturned west limb. Ben Eoligarry Mhor.

Fig. XII-27. Diagram to show the inferred relation of the direction of maximum compressive stress to the Scurrival fold.

Fig. XII-25

Fig. XII-26

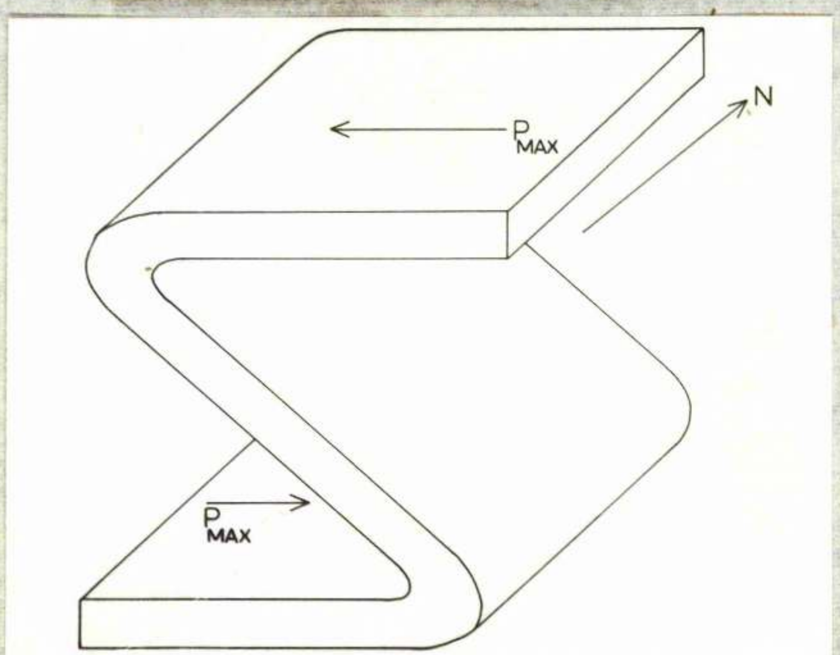


Fig. XII-27

Fig. XII-28. Vertical section looking north-east through a small F_2 style fold. Note the small pre-fold boudins rotated and jammed together during folding. South side of Traigh Mhor.

Fig. XII-29. F_2 style folds and small boudins at the top of the photograph. Shore on the east side of Scurrival peninsula.

Fig. XII-30. Diagram to show the relation of stress to the fold of Figure 28.

Fig. XII-28

Fig. XII-29

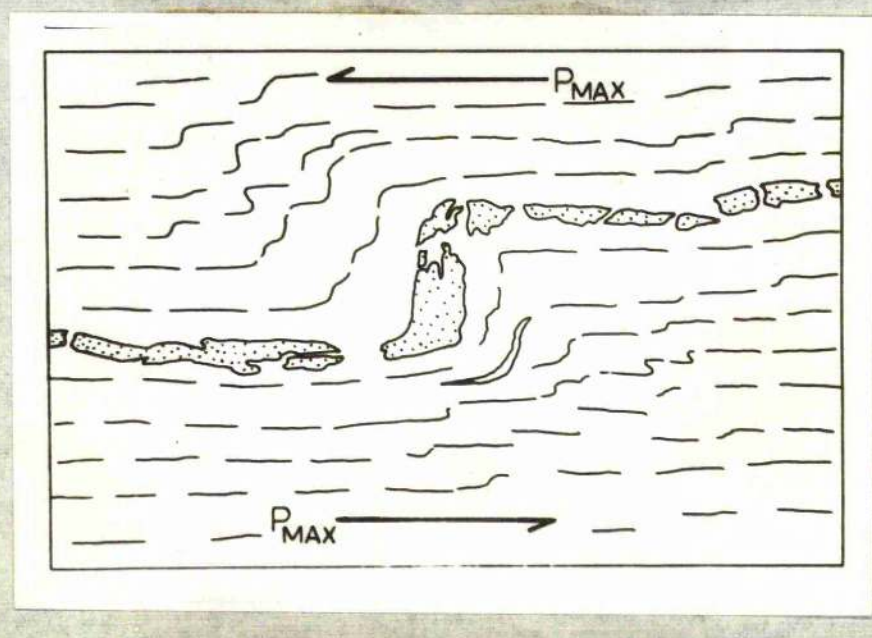


Fig. XII-30

Fig. XII-31. Three dimensional view of a fold of F_2 style crossed by other folds. South-east coast.

Fig. XII-32. Ptygmatically folded quartzo-feldspathic vein. Note the parallelism of the fainter folded vein to the left. Shore at Rudha Liath.

Fig. XII-33. Diagram to show mechanism of formation of small scale folds by plastic drag during large scale folding of rigid basic layers and plastic interfoliated quartzo-feldspathic layers. In the deeper more plastic layers, small scale quartzo-feldspathic folds are beginning to form in response to continued stress although the basic bands are unaffected.

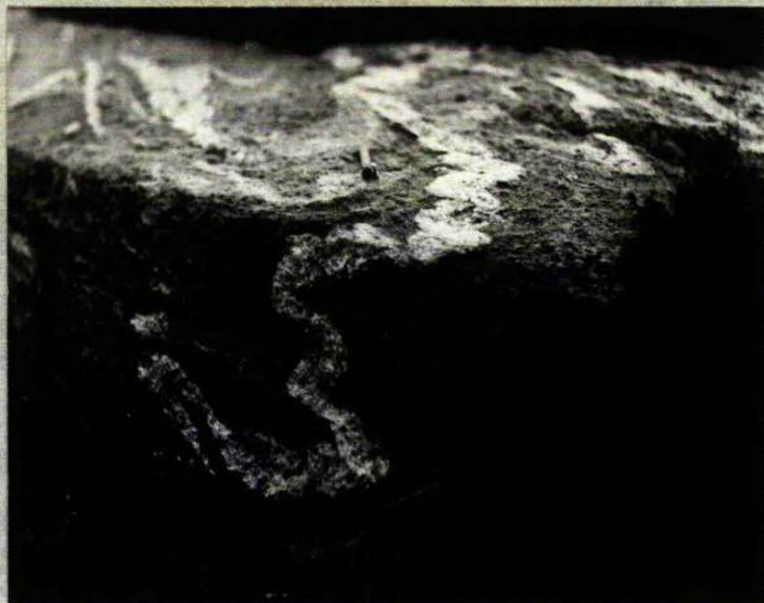


Fig. XII-31

Fig. XII-32

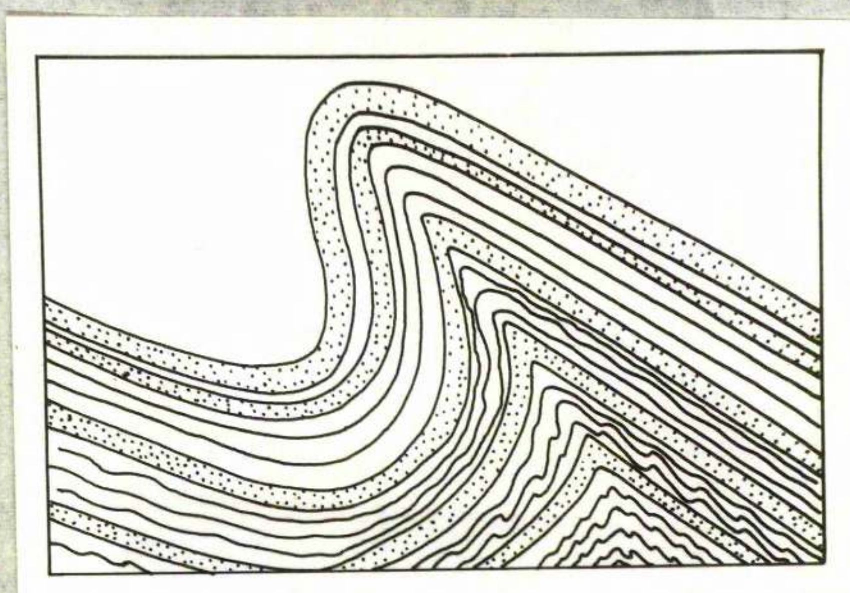


Fig. XII-33

Fig. XII-34. Diagram to show alternative mechanism for the development of plastic small scale folds on flanks of larger folds formed when basic bands (stippled) responded rigidly to deformation.

Fig. XII-35. Photograph of a section through a layered plasticine model folded on three sets of mutually perpendicular axes to simulate the complex fold pattern at Bagh nan Clach. Compare figure II-1.

Fig. XII-36. Diagrammatic representation of the first two folds leading to the formation of complex structures of the type occurring at Bagh nan Clach.

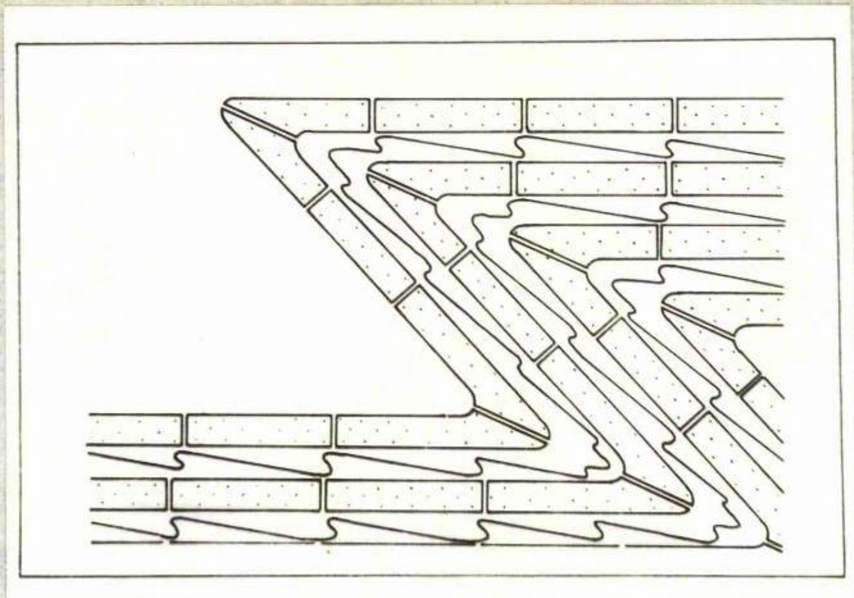


Fig. XII-34

Fig. XII-35

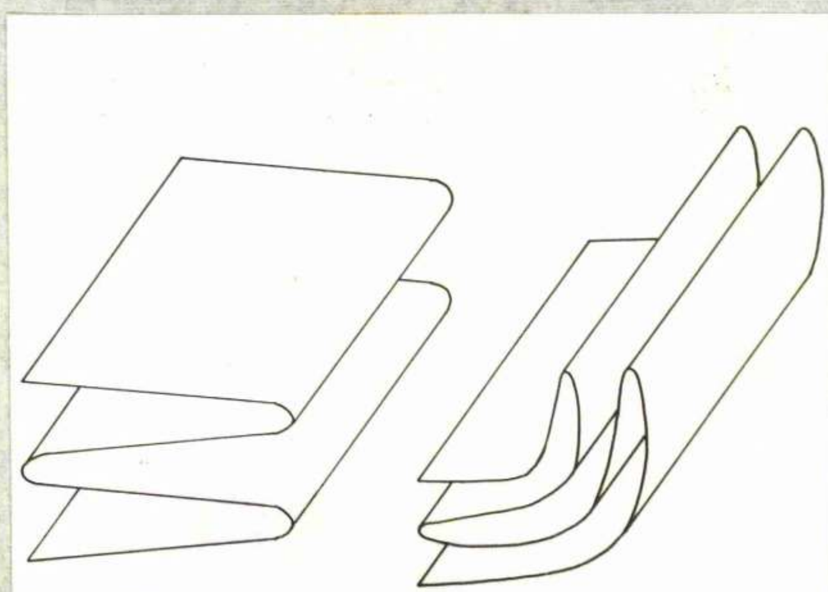


Fig. XII-36

Fig. XII-37. Diagrammatic representation of the effect of a third set of folds on the first two to form the complex fold of the type at Bagh nan Clach. Before compression to the final tight form.

Fig. XII-38. A block diagram to show the relationships of complex folds of the type at Bagh nan Clach to the large scale structure.

Fig. XII-39. Core of fold showing comparatively planar, unsheared nature of the limbs (lower left of photograph) compared with the crenulate foliation at the hinge. Rudha Glas.

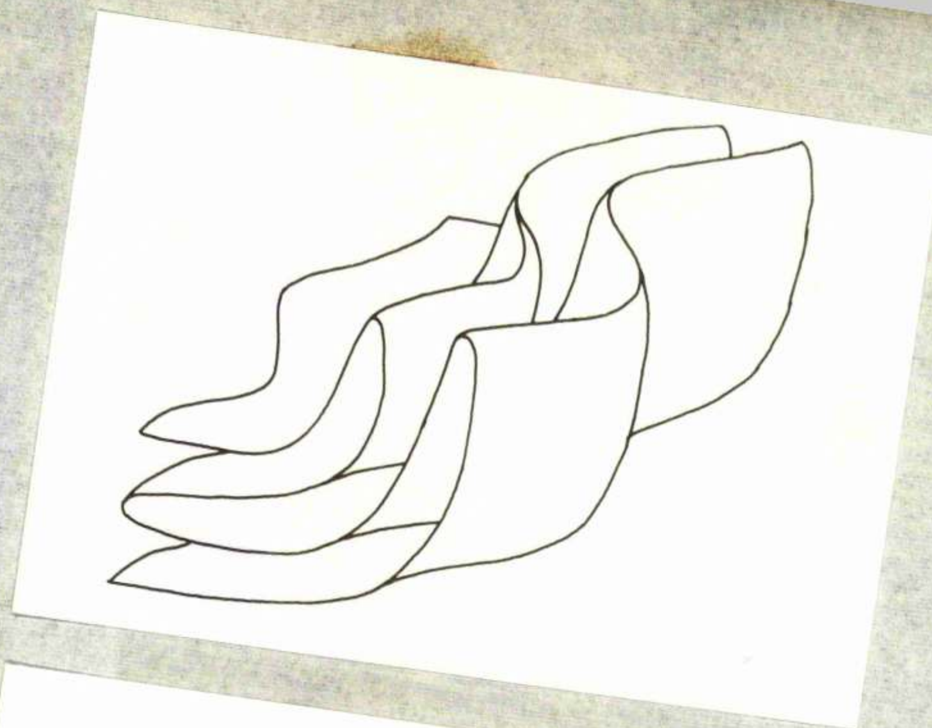


Fig. XII-37

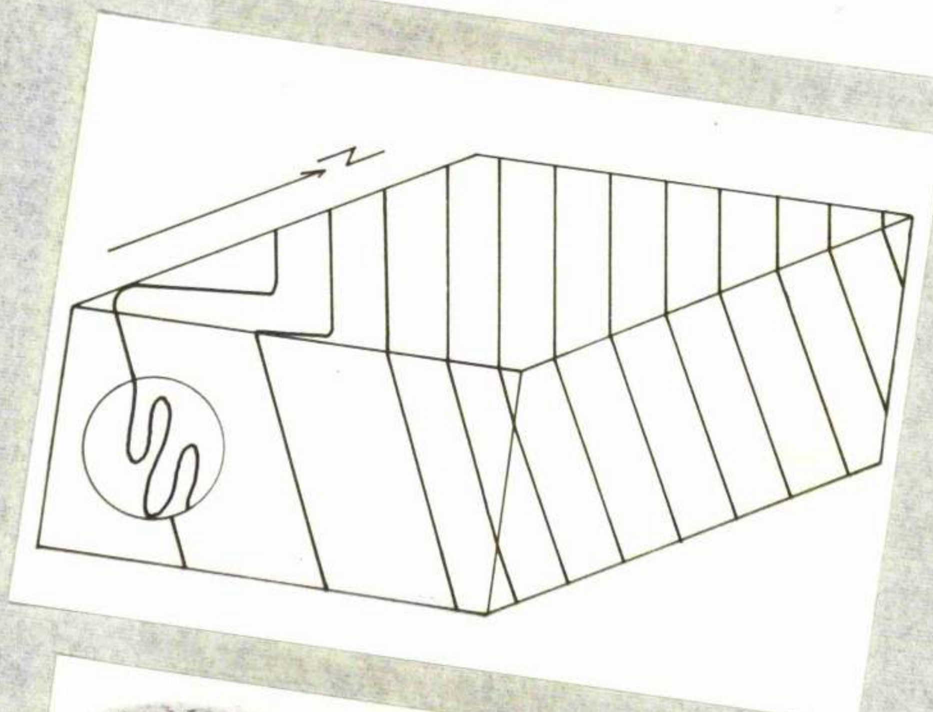


Fig. XII-38

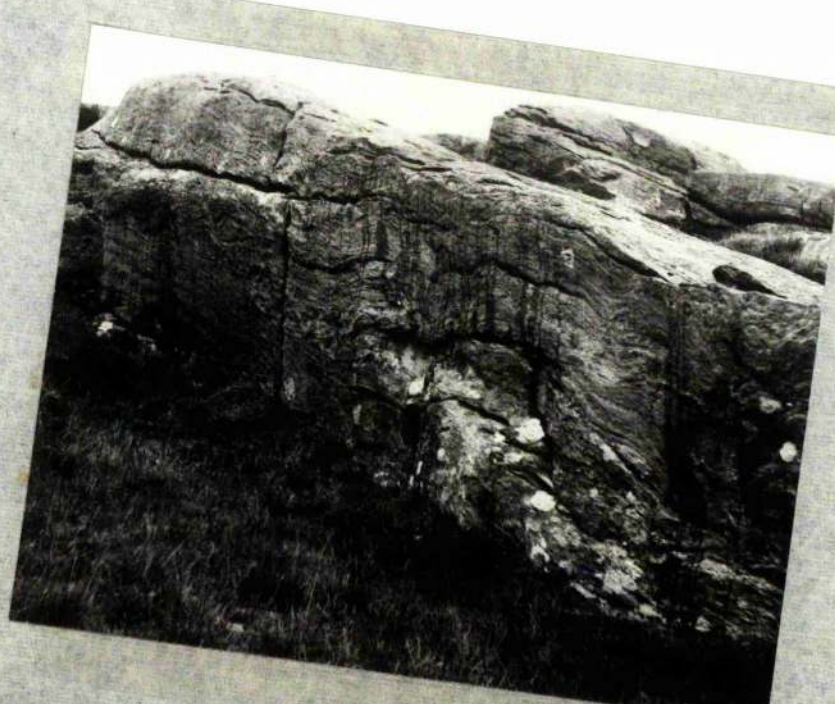


Fig. XII-39

Fig. XII-40. Diagram to show the effect of topography on fanning out of the folds on the map at Scurrival. The outcrop of a fold on a surface sloping slightly less than the fold axial plunge (thick line) compared with that on a horizontal surface (thin line).

Fig. XII-41. Mesoscopic F_2 fold. View looking north shore on north side of Orosay Traigh Mhor.

Fig. XII-42. β-diagram of 63 foliation attitudes (1354 points) from an arbitrarily selected area outside the hinge region of the Scurrival structure on the west coast, south of Scurrival Point. Two elongate maxima plunging at approximately 15° towards 345° and 25° towards 175° define the F_2 axis. Curvature of these maxima is due to later folding about 145° (F_3) and north-east (F_5) axes and elongation as an incomplete girdle striking approximately north results from folding on E.-W. (F_4) axes. Contours at 1%, 2.5%, 5% and 7.5% intervals.

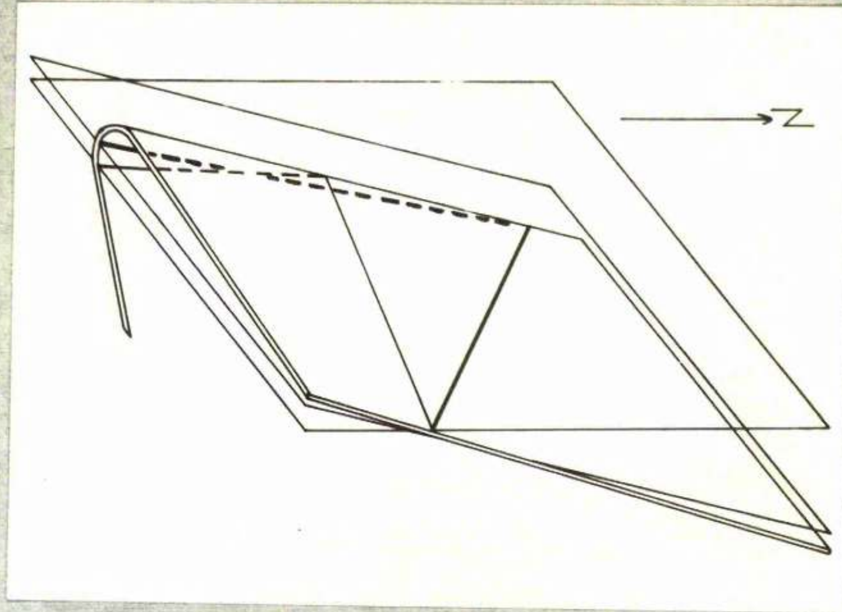


Fig. XII-40

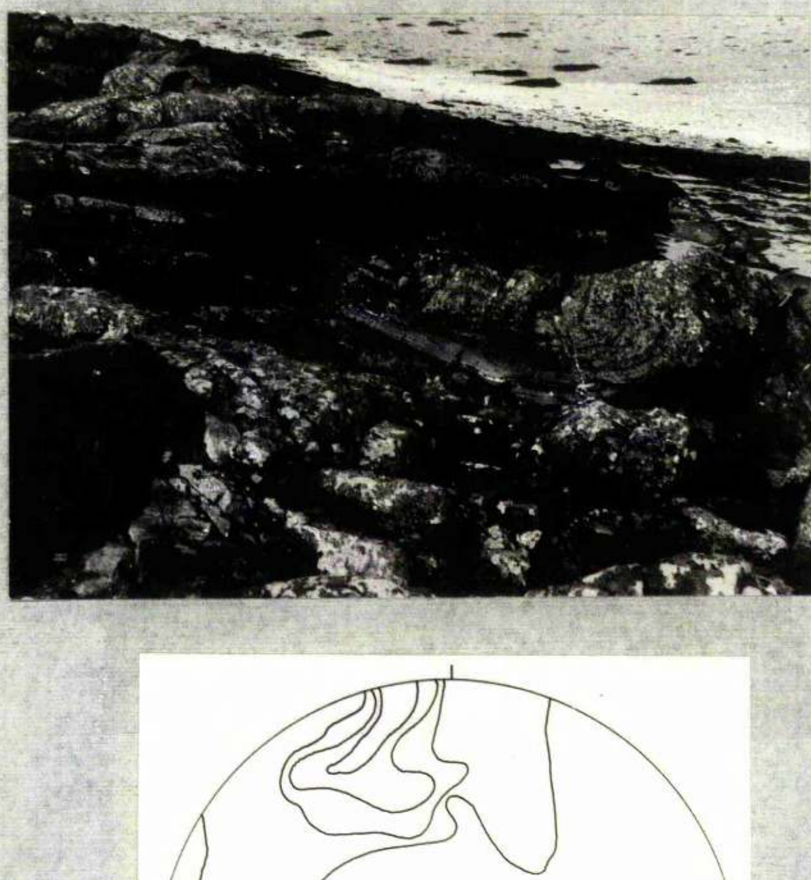


Fig. XII-41

Fig. XII-42

Fig. XII-43. Diagram of the Scurrival structure. F_3 lineation, F_4 folds and F_5 folds have been superimposed on the F_2 structure.

Fig. XII-44. A large mesoscopic F_2 fold excavated by wave erosion. This shows the north-east dipping axial plane, the gently north dipping limbs, the overturned limb and gently north plunging axis. West coast Mingulay.

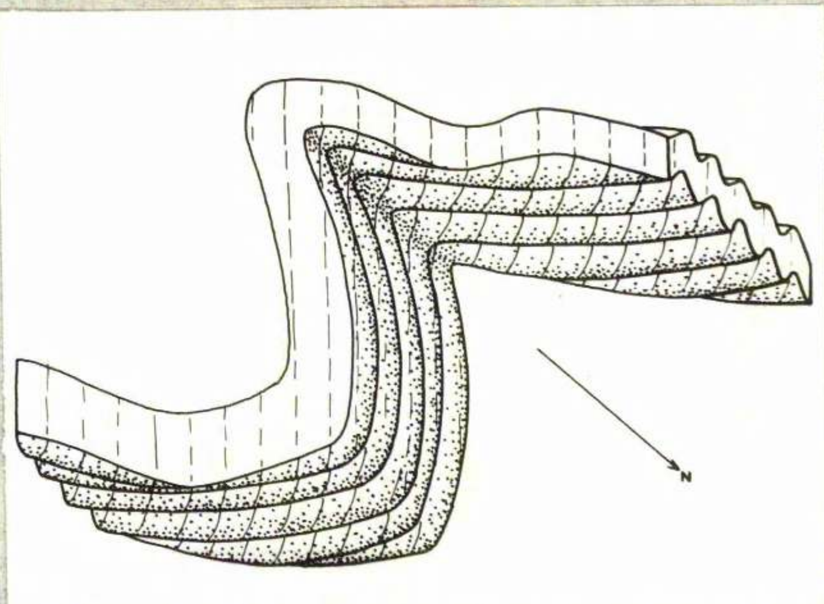


Fig. XII-43

Fig. XII-44

Fig. XIII-1. Lineation and small folds trending 150° parallel to the pencil crossing shallow 100° trending folds. Shore at Halaman Bay. Note the lineation due to alignment of hornblendes parallel to early isoclinal folds at lower left.

Fig. XIII-2. Lineation parallel to 150° cutting across foliation. View looking towards 150°. Beach at Halaman Bay.

Fig. XIII-3. Lineation parallel to F_3 fold axes trending 150°. Beach near the west end of Halaman Bay. The apparent steepness of the fold limbs is due to the attitude of the exposure surface.

Fig. XIII-1

Fig. XIII-2

Fig. XIII-3

Fig. XIII-4. Equal area plot of small fold axes (circles) and lineations.

Fig. XIII-5. Plot of F_3 lineations (dots) and cyclographic plots of F_4 folds from the east end of the beach at Halaman Bay to show how F_4 folding has caused dispersion of F_3 lineations.

Fig. XIII-6. Equal area plot of attitudes of lineation (circles) and poles to foliation from the east end of Halaman Bay.

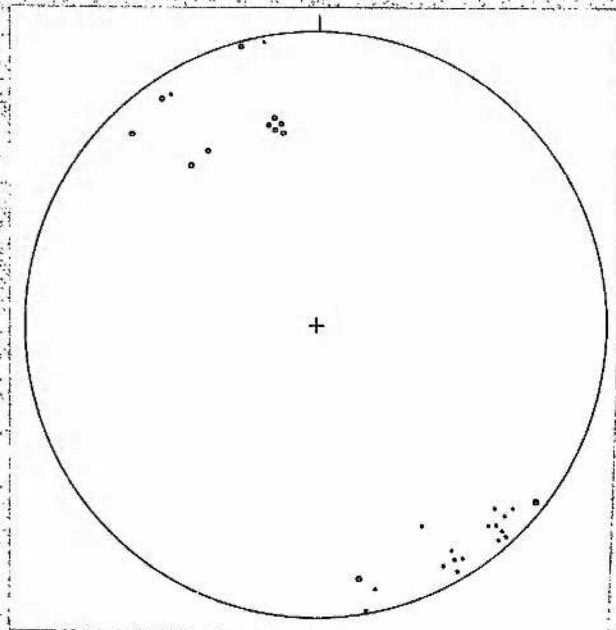


Fig. XIII-4

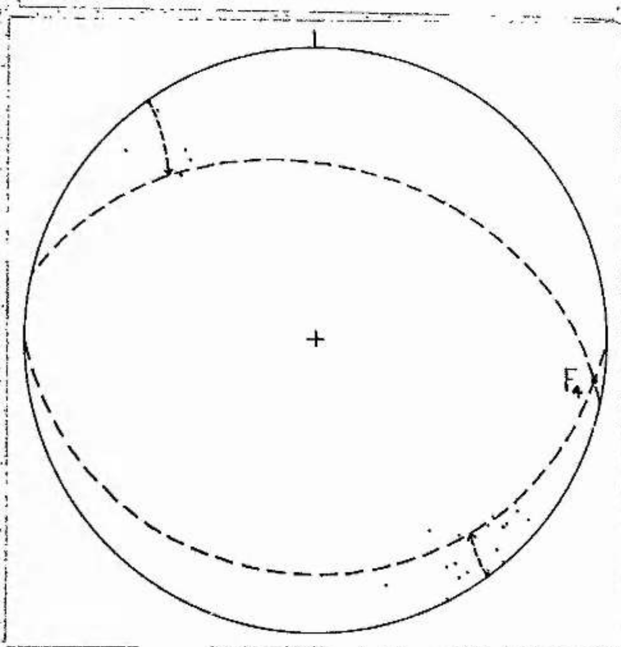


Fig. XIII-5

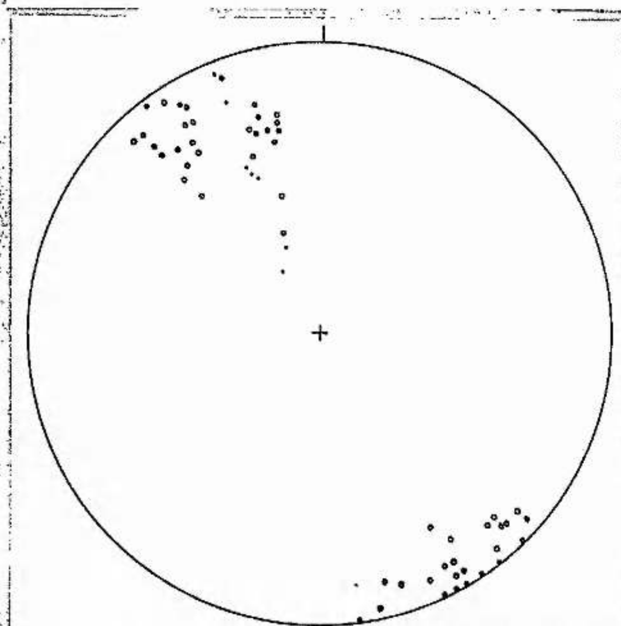


Fig. XIII-6

Fig. XIII-7. Equal area plot of 260 quartz [0001] axes from an oriented specimen collected at the beach at Halaman Bay. Contours at 1%, 15%. 2% and 3% intervals.

Fig. XIII-8. Equal area plot of 560 quartz [0001] axes from a oriented specimen collected at random south of Castlebay. Contours at 1%, 2%, 3% and 4% intervals.

Fig. XIII-9. Equal area plot of poles to (001) cleavage on 550 biotite grains from a vertical section facing northwest. Dashed lines indicate the traces of the foliation. β is the intersection of girdles to the double maximum and is parallel to the lineation B . Specimen from the beach at Halaman Bay. Contours at 2.5%, 5%, 7.5%, 10% and 12% intervals.

Fig. XIII-7

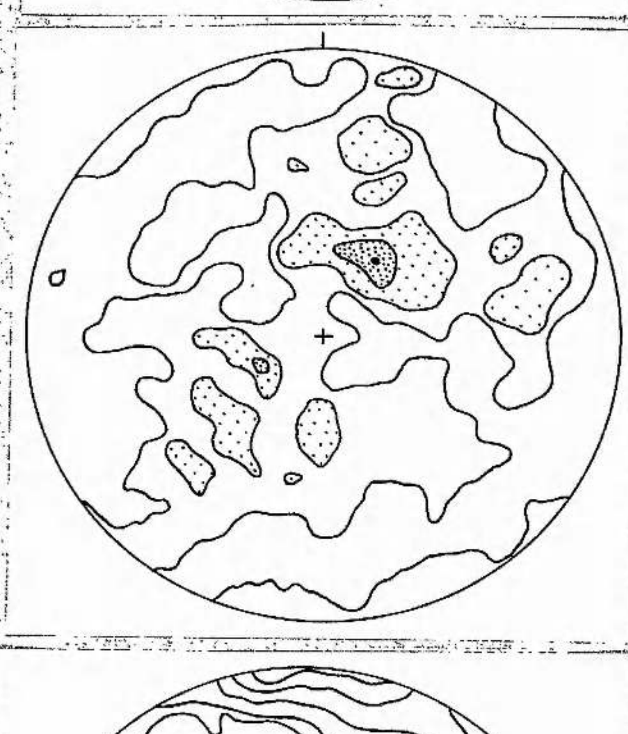


Fig. XIII-8

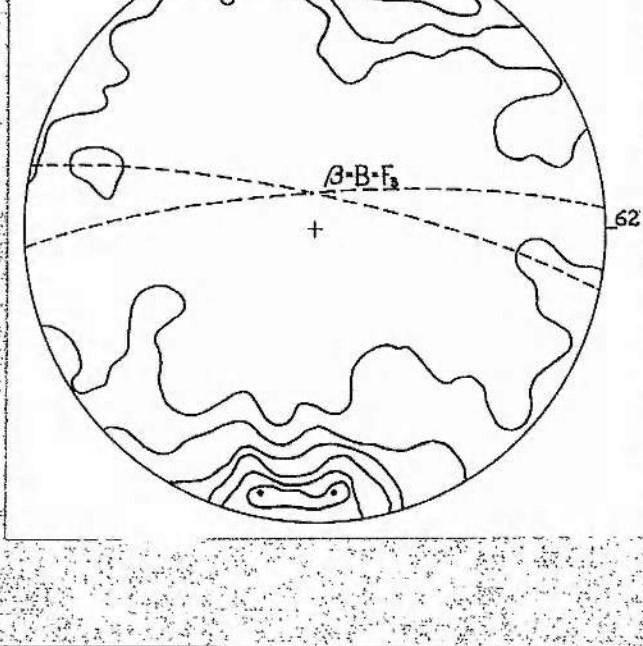


Fig. XIII-9

Fig. XIII-10. Folds of about 18 inch wavelength fluted by parallel 3 inch wavelength folds plunging towards 150°. Roadside east of the Church of Scotland, Castlebay.

Fig. XIII-11. Small folds trending approximately 150° crossed by 100° lineation parallel to the pencils. Vaslain.

Fig. XIII-12. Trends of fine lineation measured on the shore at Allasdale.

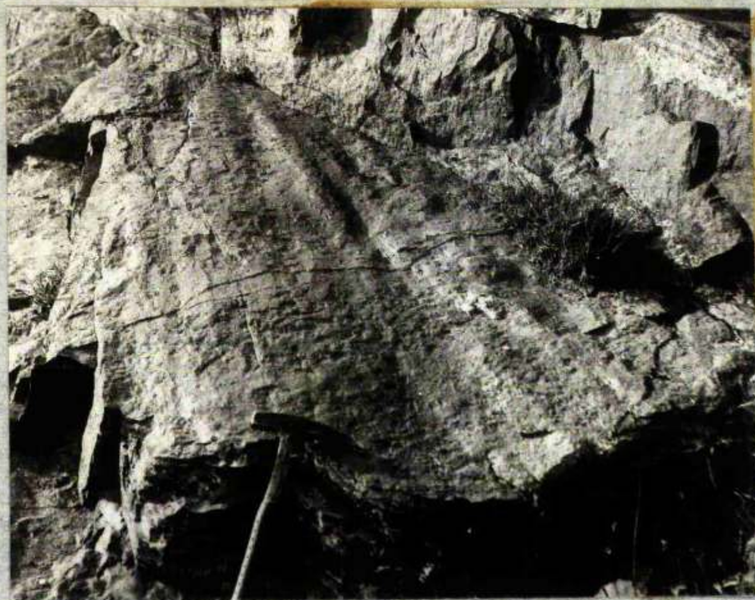


Fig. XIII-10

Fig. XIII-11

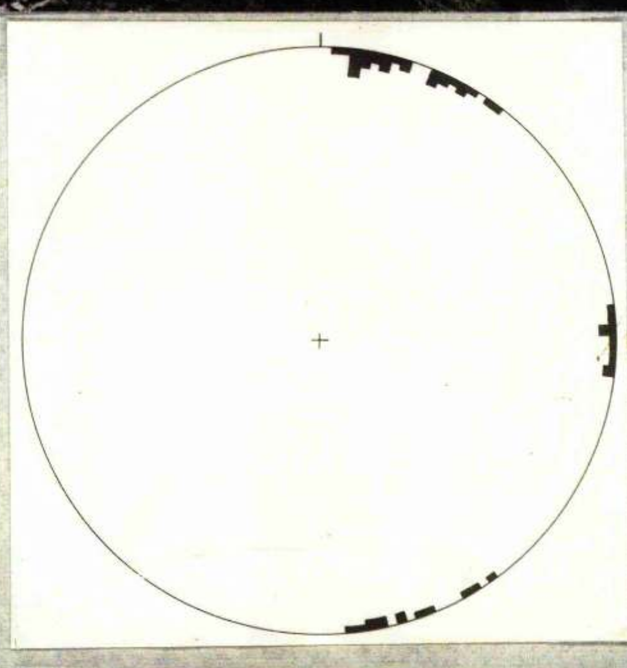


Fig. XIII-12

Fig. XIV-1. Gently east plunging, almost symmetrical, open style F_4 folds exposed by shear parallel to the foliation. Note repeated bifurcation to the right of the picture which suggests that some folds may be conjugate. Shore south of Bagh nan Clach.

Fig. XIV-2. Almost parallel, approximately 100° trending axial planar traces intersecting to the right showing asymmetry of fold style due to gentle north-east dip of foliation. Beach at Halaman Bay.

Fig. XIV-3. Small folds trending approximately 100° in migmatite. Note oblique intersection of axial planar traces below pencil, and growth of feldspar porphyroblasts in the migmatite. Above the shore north of Rudha Liath.

Fig. XIV-1

Fig. XIV-2

Fig. XIV-3

Fig. XIV-4. Diagram to show variation in style of F_4 folds with position relative to the attitude of the foliation.

Fig. XIV-5. Style of 100° trending folds. Note attenuation to left of photograph. Shore at Bagh nan Clach.

Fig. XIV-6. Style of 100° trending folds. Shore at Bagh nan Clach.

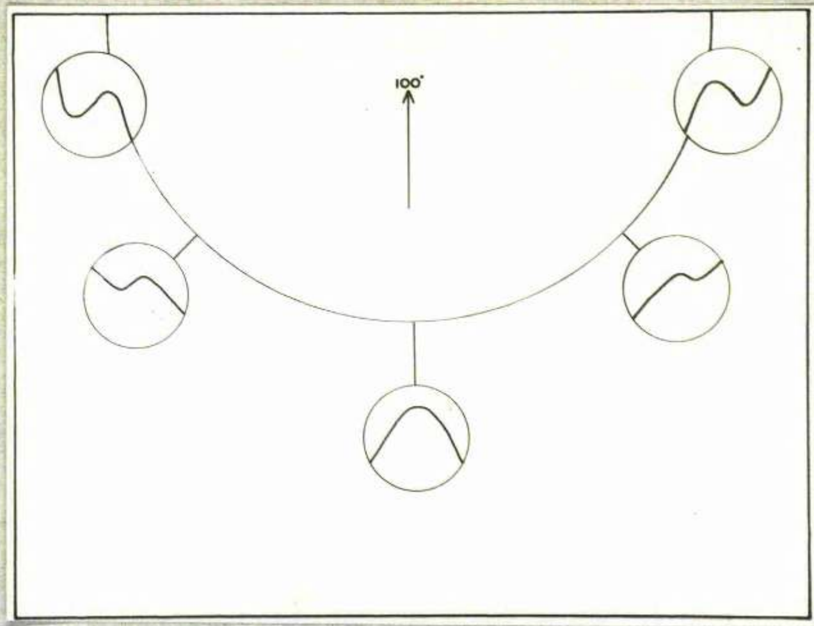


Fig. XIV-4

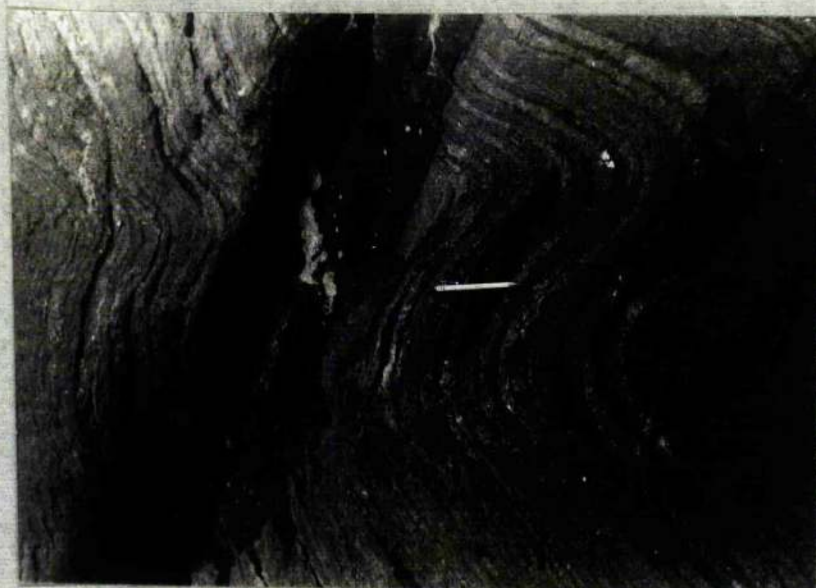


Fig. XIV-5

Fig. XIV-6

Fig. XIV-7. Asymmetrical, 100° trending folds showing development of migmatite parallel to their axial surfaces. The foliation dips to the north-east and the south limbs of the synforms are steeper. View looking east. Beach at Halaman Bay.

Fig. XIV-8. Small folds plunging to 280° showing asymmetry due to general attitude of foliation. Here the foliation dips south-west and synforms have steep north limbs. View looking east. Coast south-west of Doirlinn.

Fig. XIV-9. Small folds trending 100° showing incipient migmatization parallel to their axial surfaces. The isoclinally folded nature of the foliation is distinctly visible. View looking east. Tangusdale, east of the road.

Fig. XIV-7

Fig. XIV-8

Fig. XIV-9

Fig. XIV-10. Folds plunging to 280° associated with small boudins (centre). View looking west. Beach on north shore of Fiary.

Fig. XIV-11. Photograph to show the effect on the style of the attitude of the outcrop surface on 100° trending folds. Boulder Traigh Mhor.

Fig. XIV-12. Disharmonic, ptygmatic style of folded quartzo-feldspathic vein. Bagh nan Clach.

Fig. XIV-10

Fig. XIV-11

Fig. XIV-12

Fig. XIV-13. "Conjugately" refolded isoclinal folds viewed along the axes parallel to 100^{o}. Note however, that individual axial planes all dip in the same sense, to the south (right). View looking east. West coast of Fiary.

Fig. XIV-14. Pinch-and-swell structures plunging at 20^{o} towards 310^{o} in quartzo-feldspathic gneiss. View looking west, Rudha Mhor.

Fig. XIV-15. Diagram to show inferred stress system responsible for F_4 flexural folds.

Fig. XIV-13

Fig. XIV-14

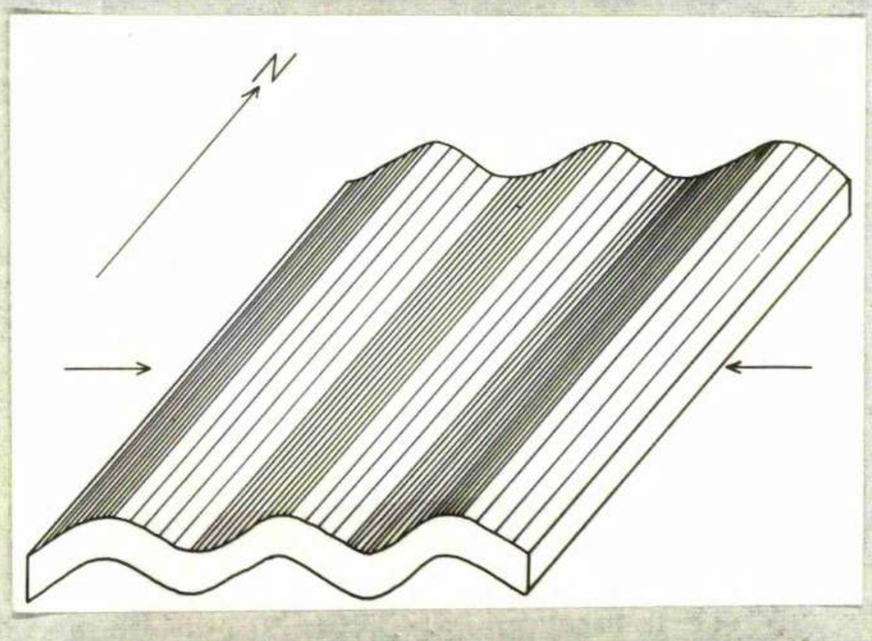


Fig. XIV-15

Fig. XIV-16. Diagram of inferred local stress system which produced folding and pegmatite flow between the boudins of figure IX-5. P_1 slightly greater than P_2.

Fig. XIV-17. Diagram to show end drag on boudins by lateral flow of migma between boudins.

Fig. XIV-18. Diagram to show the development of corrugation related to boudins in response to later lateral compression.

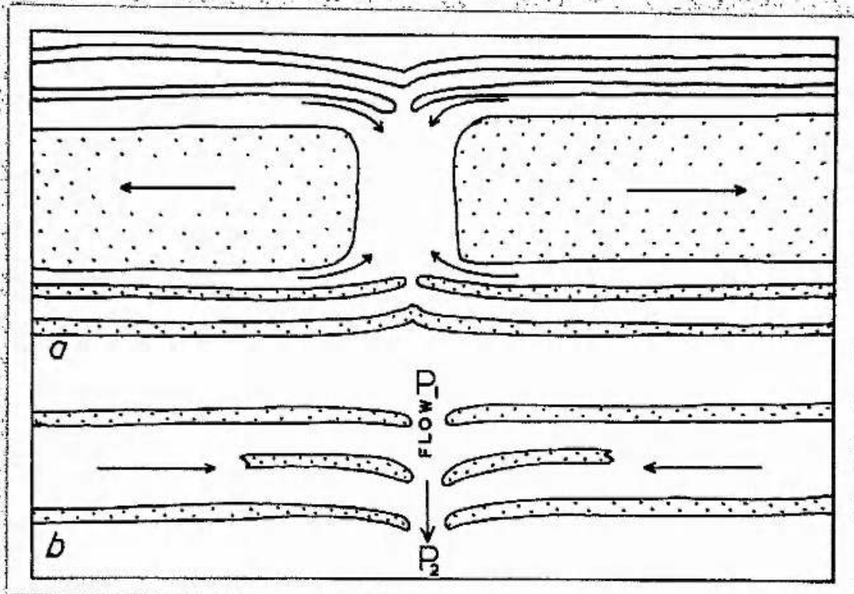


Fig. XIV-16

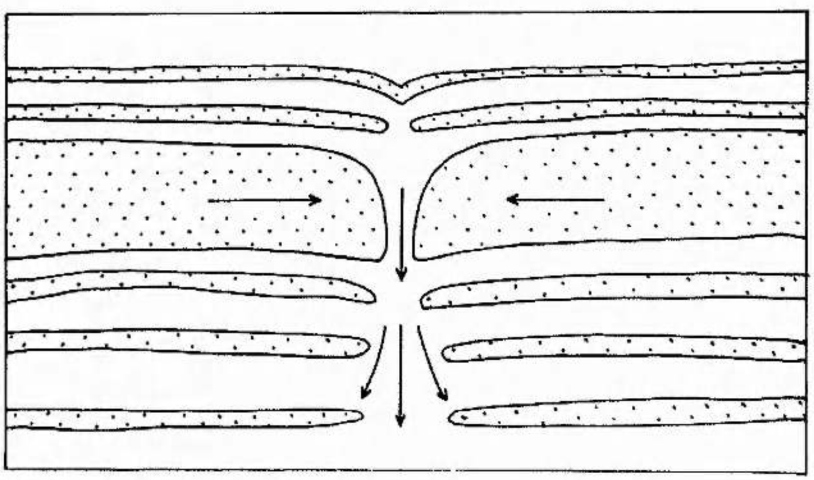


Fig. XIV-17

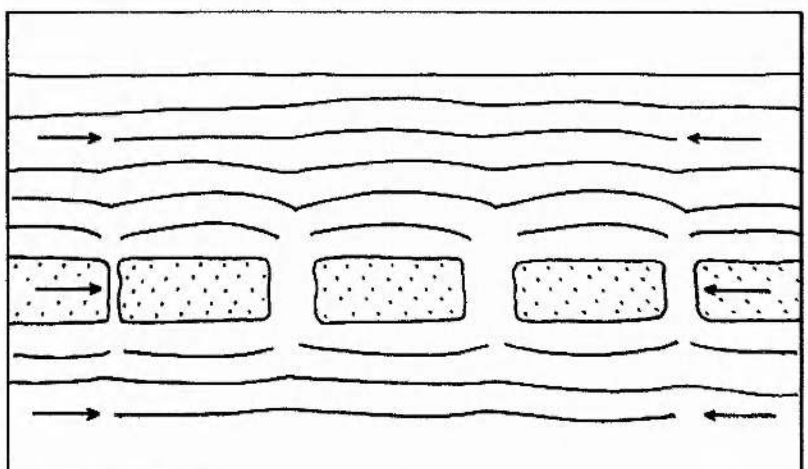


Fig. XIV-18

Fig. XIV-19. Diagram to show development of boudinage and corrugation related to boudins by compression directed perpendicular to the foliation.

Fig. XIV-20. Diagram to show inferred direction of compression which formed the boudins.

Fig. XIV-21. Diagram to show relationship between stress fields necessary to form boudins and parallel flexural folds. (a). Formation of boudins, (b) Rotation to their present attitude by folding.

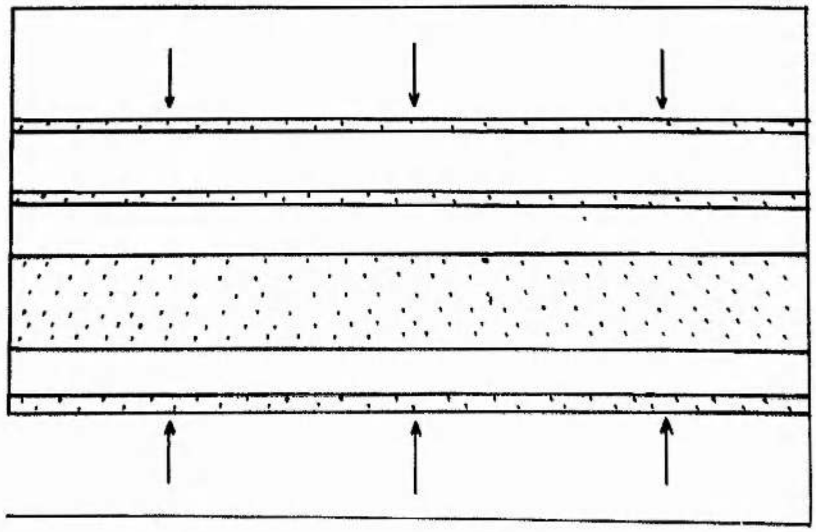


Fig. XIV-19

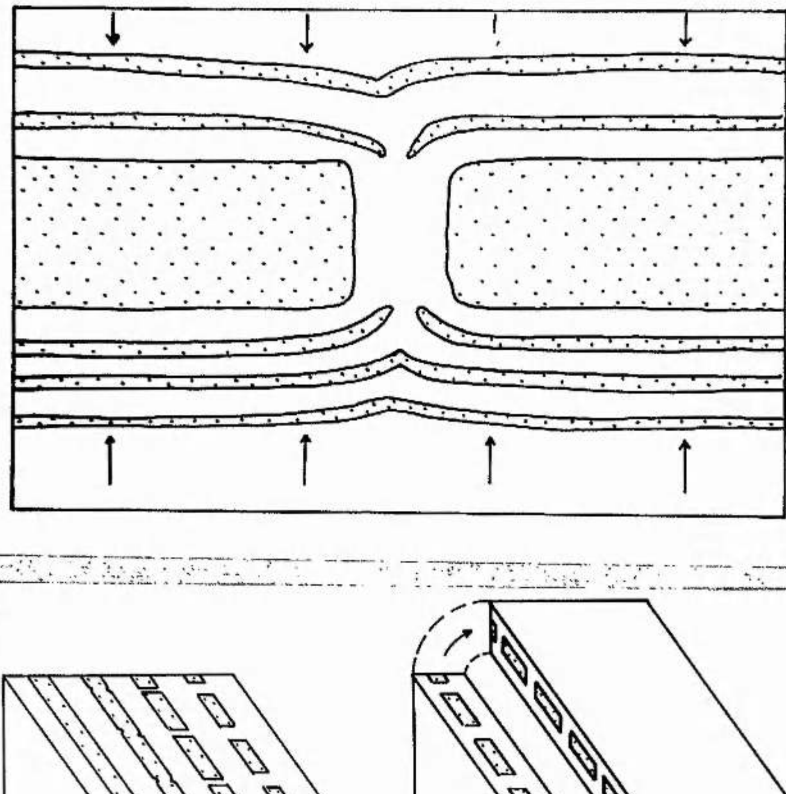


Fig. XIV-20

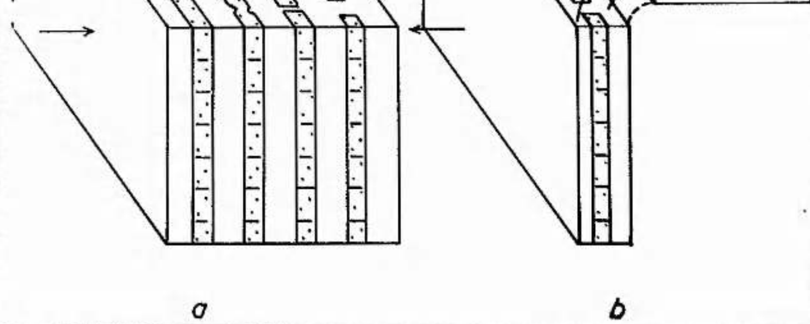


Fig. XIV-21

Fig. XIV-22. Diagram of N.-S. directed compression which amplified already formed 100° trending folds associated with boudinage.

Fig. XIV-23. Ribs striking 100° (parallel to the hammer handle) which are curved in the right foreground probably due to foliation shear. The foliation strikes diagonally away to the right. View looking southeast. Bagh nan Clach.

Fig. XIV-24. Ribs striking 100° cutting migmatite and pegmatite (under hammer). The foliation can be seen striking away to the left. Note that the ribs are not developed in the lower left hand corner and immediately to the right of the hammer, evidently having been obliterated during later anatexis. View looking west. North of Ben Eoligarry Mhor.

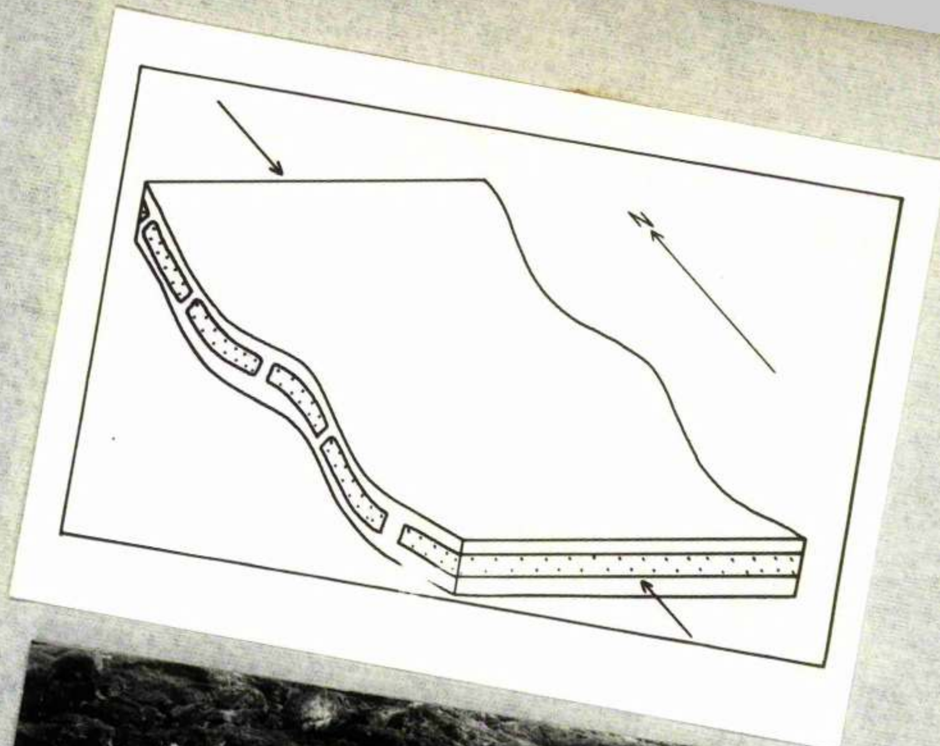


Fig. XIV-22

Fig. XIV-23

Fig. XIV-24

Fig. XIV-25. Ribbing due to septa striking 100^{o}, cutting basic and acid gneisses. View looking east. Bagh nan Clach.

Fig. XIV-26. Ribs on quartzo-feldspathic gneiss striking 100^{o} and to 120^{o}. Foliation strikes away to the right. View looking east. North slope of Ben Eoligarry Mhor.

Fig. XIV-27. Diagram to show the relationshipbetween cross cutting septa and possible stress conditions due to late E.-W. compression.

Fig. XIV-25

Fig. XIV-26

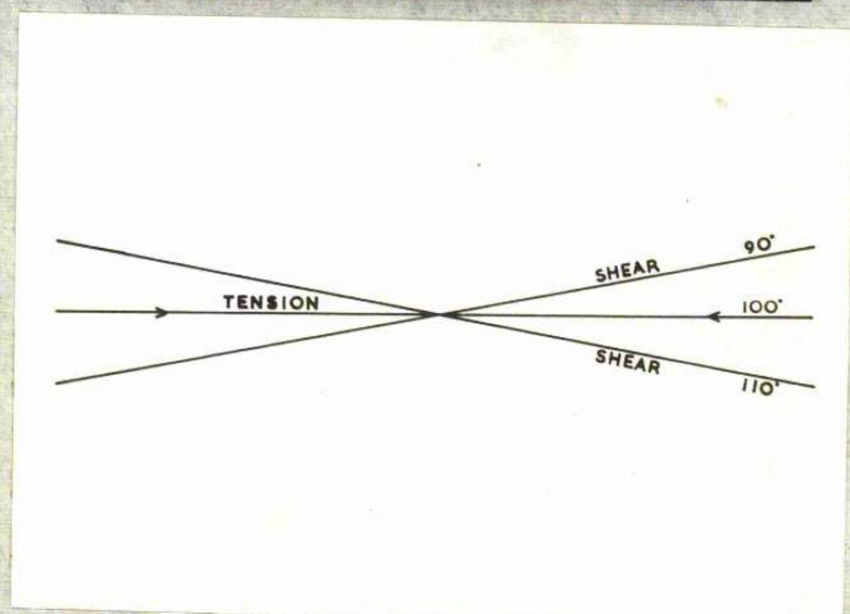


Fig. XIV-27

Fig. XIV-28. Migmatite crossed by faint ribs striking 120° parallel to the pencil. View looking west. Shore at Eoligarry.

Fig. XIV-29. Ribs due to 100° trending septa showing fracturing through centre. Quartzo-feldspathic veins in the background appear to cut the ribs. View looking east. Bagh nan Clach.

Fig. XIV-30. Photomicrograph of a thin section through a 100° striking septum. Bagh nan Clach. x 40. Plane polarized light. Within the rib (top of figure) both hornblende and feldspar are shattered and clouded, and the feldspar is replaced by clinozoisite.

Fig. XIV-28

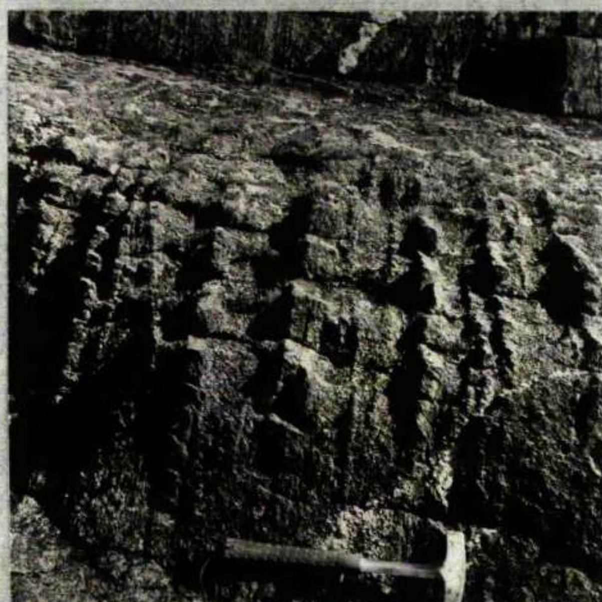


Fig. XIV-29

Fig. XIV-30

Fig. XIV-31. Remnants of F_2 folds (at hammer) crossed by faint 100° lineation. View looking east. Shore at Bagh nan Clach.

Fig. XIV-32. Loose block fractured along thin pegmatite veins perpendicular to the foliation, showing thinning of the foliation nearest the pegmatite veins due to squeezing-out of fluid quartzo-feldspathic migma from the bands due to compression perpendicular to the foliation during anatexis. The remnants of early isoclinal folds can be seen above the hammer handle. Beach at Mingulay Bay, Mingulay.

Fig. XIV-33. Conjugate style of folding due to the convergence of F_2 and F_4 fold axes. View looking towards 70°. Guarsay Mor, Mingulay.

Fig. XIV-31

Fig. XIV-32

Fig. XIV-33

Fig. XIV-34. Curvature of trend of F_4 fold axis from 85°, nearest the camera to 115° around an F_5 fold plunging gently to 55°. Hammer shaft is parallel to 45°. View looking towards 90°. Guarsay Mor, Mingulay.

Fig. XIV-35. Curvature of F_2 axial plane from 72° towards the north-east (top) to 50° to the south-west (bottom) by a later F_4 fold. View looking towards 300° parallel to the trace of the axial planar pegmatite vein. Note, however, that the fold axis plunges at approximately 45° towards 345°. Hecla Point, Mingulay.

Fig. XIV-34

Fig. XIV-35

Fig. XV-1. Broad shallow style of the late north-east plunging folds of F_5 phase. Very faint linear features dipping steeply to the right (east) can be seen to the left on the band below the hammer. View looking north-east. Halaman Bay.

Fig. XV-2. Style of late north-east folding. View looking east. Scurrival Point.

Fig. XV-3. Diagram to show the relationship of septa to the fold axial trend during the late north-east folding F_5. To show that vertical septa are unlikely to be affected by sub-horizontal late north-east fold axes.

Fig. XV-1

Fig. XV-2

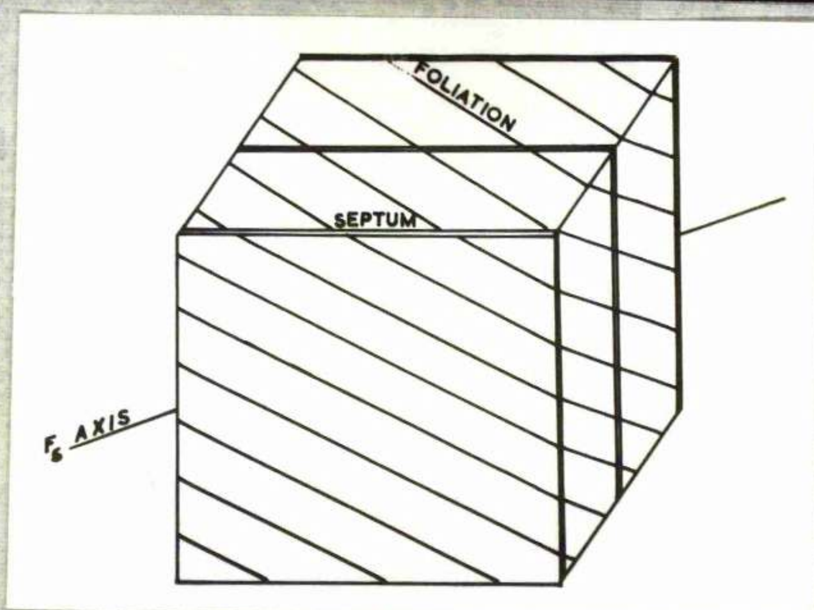


Fig. XV-3

Fig. XV-4. Core of antiform on the shore south of Brevig showing the contorted nature of small isoclinal folds.

Fig. XV-5. Small north-east plunging fold showing traces of relict axial planar cleavage. View looking north-east. South-east coast.

Fig. XV-4

Fig. XV-5

Fig. XVI-1. View of Castlebay from the south-east showing the small scarp at the outcrop of the Thrust sole on the hill behind.

Fig. XVI-2. Outcrop of a subsidiary Thrust sole close to the northern limit of the overthrust sheet. Behind the School, Loch Obe.

Fig. XVI-3. Shear surfaces exposed on an east striking vertical joint. South-west flank of Heaval.

Fig. XVI-1

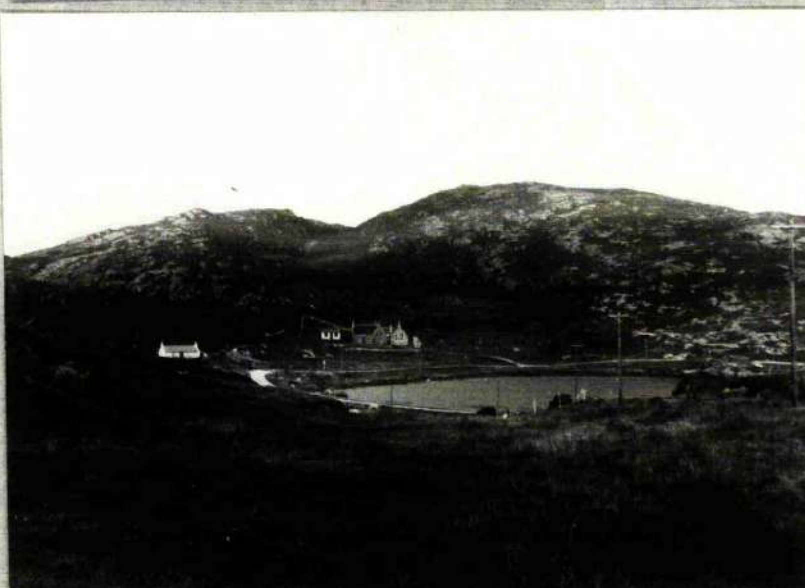


Fig. XVI-2

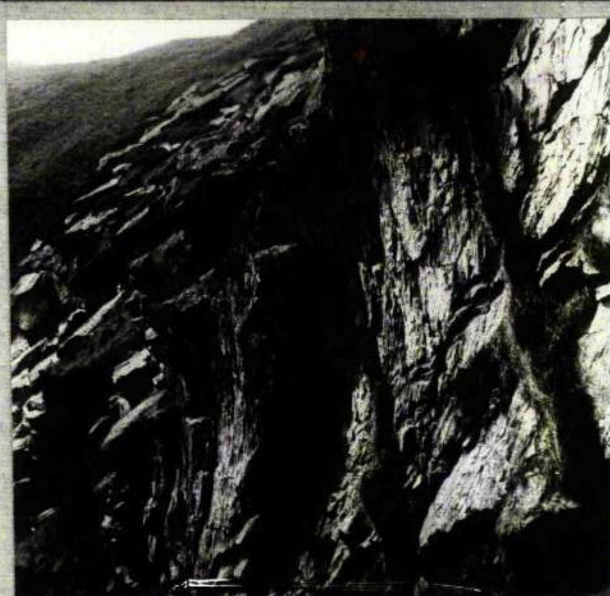


Fig. XVI-3

Fig. XVI-4. Diagram to show the position of the scarp exposing sigmoidal tension gashes in relation to the Heaval Thrust.

Fig. XVI-5. Sigmoidal tension gashes in a vertical joint face. South-west flank of Heaval.

Fig. XVI-6. Relationship between tension gashes, shear surfaces and stress. (a). Tension gashes. (b). Shear surfaces.

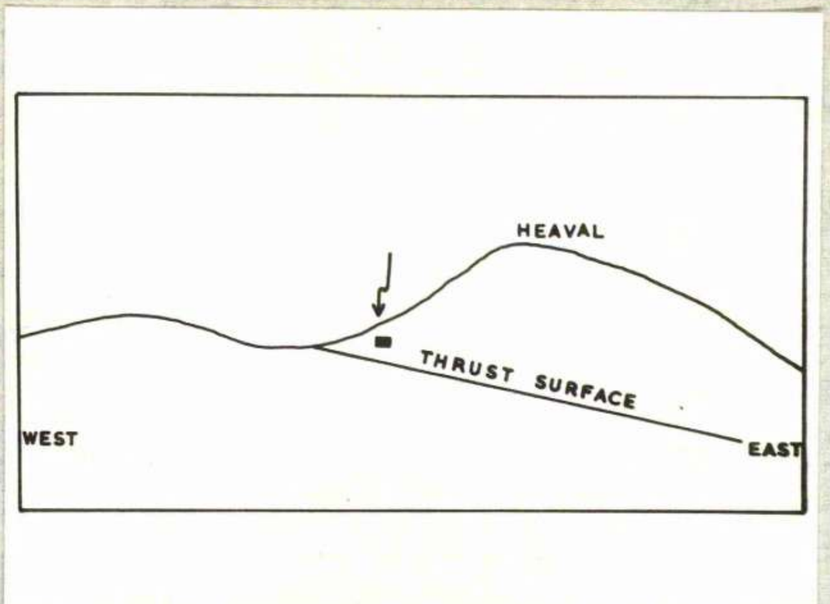


Fig. XVI-4

Fig. XVI-5

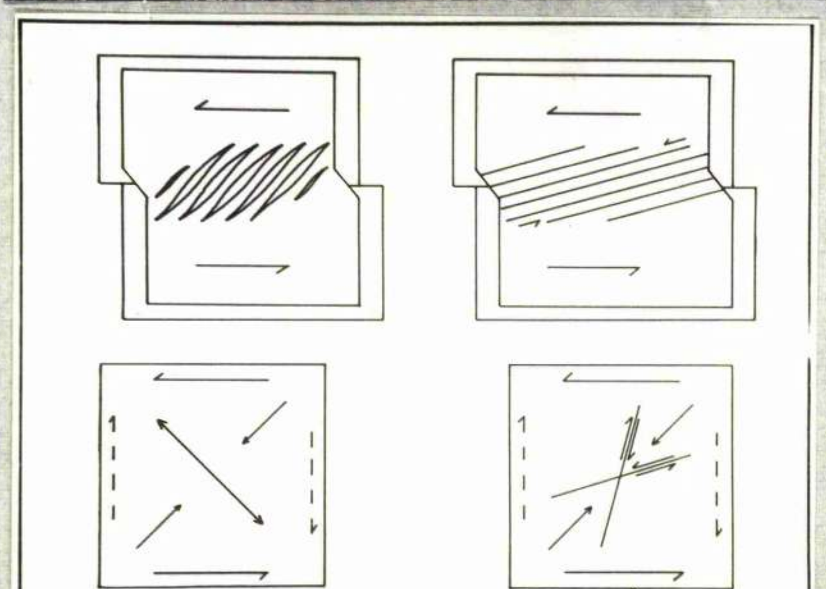


Fig. XVI-6

Fig. XVI-7. Average attitude of sigmoidal tension gashes, and the derived attitude of the Thrust direction. Heaval.

Fig. XVI-8. Map to show the trace of the Thrust outcrop and its positions and altitudes at Heaval and Beinn Mhartuin.

Fig. XVI-9. Beinn Mhartuin from the south-east showing the gentle eastern slope parallel to the Thrust sole. Greian Head can be seen in the top right corner. Borve valley.

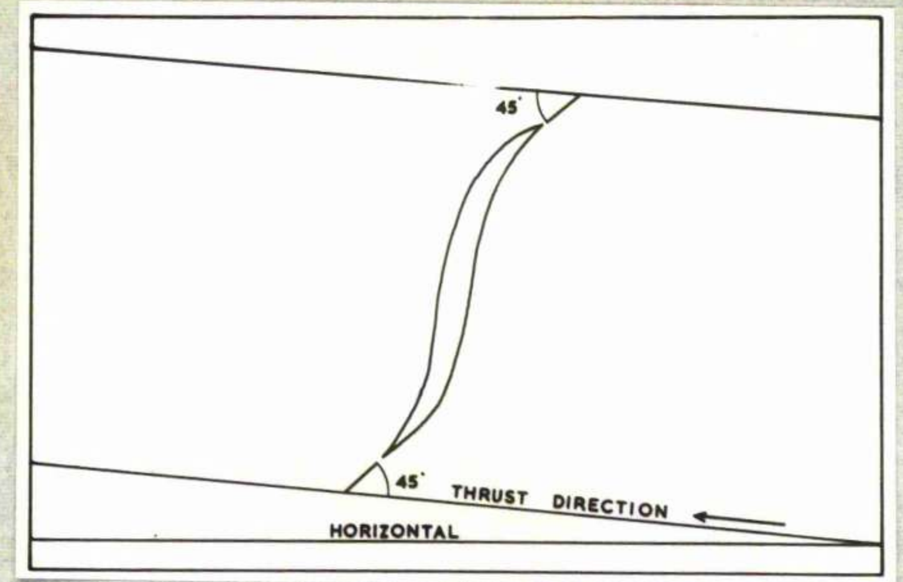


Fig. XVI-7

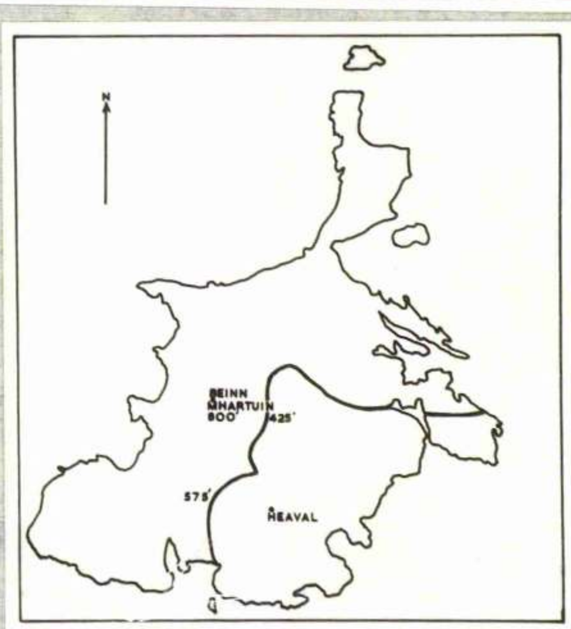


Fig. XVI-8

Fig. XVI-9

Fig. XVI-10. Block diagram to show how rotation has affected the overthrust block. a) Segment of the overthrust block to show the attitudes of the direction of thrusting and the Thrust sole. b) The resultant of the Thrust and gravity forces to show the direction of movement. c) A vertical projection onto the Thrust sole of the Thrust segment to show the effects of thrust acting at the centre of gravity of the block (P) and drag, acting through the centre of the base (C). The two forces produce a clockwise rotational couple.

Fig. XVI-11. A finely jointed pseudotachylite pavement striated parallel to the pencil. Hillside south side of road at Cuier.

Fig. XVI-12. Flinty crush-breccia of acid and intermediate quartzo-feldspathic gneiss seamed by dark pseudo-tachylite veins. Greian.

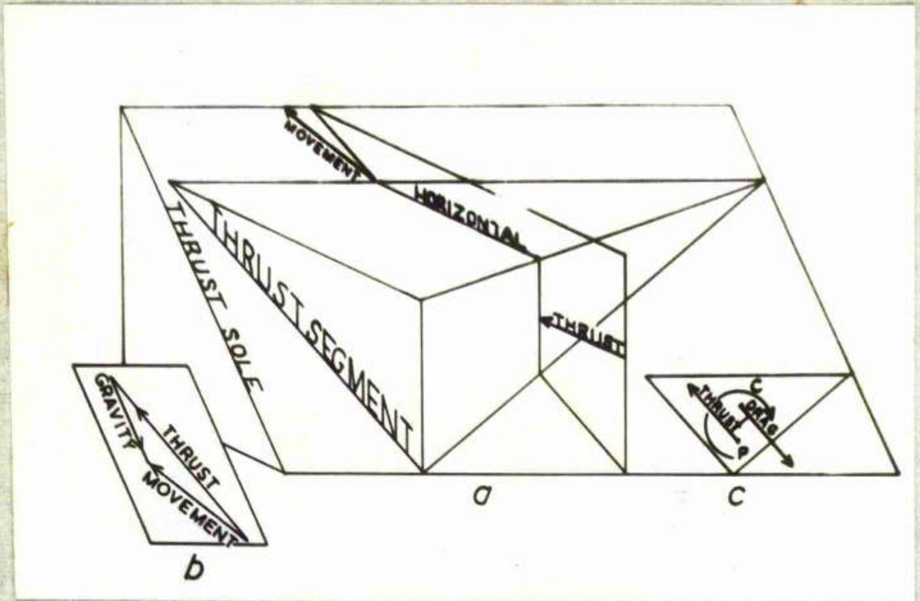


Fig. XVI-10

Fig. XVI-11

Fig. XVI-12

Fig. XVI-13. Small bifurcating pseudotachylite vein showing flow banding (above coin). Hillside north of Northbay School, Loch Obe.

Fig. XVI-14. Aerial photograph of Bruernish Peninsula (approximate scale 1:10,560) to show pattern of steep to vertical master joints.

Fig. XVI-13

Fig. XVI-14

Fig. XVII-1. Thrusting following normal faulting. The layer of intermediate gneiss has clearly been faulted normally on a plane dipping steeply to the left (east) and then a wedge of the lowest basic gneiss and the banded gneiss on the right has been driven in below that on the left. View looking north. East end of beach at Cliad.

Fig. XVII-2. Vertical N.-S. tension jointing below the Thrust, exposed in an east-striking vertical joint face west of Heaval. View looking south.

Fig. XVII-3. Regular, 80° striking jointing on the south coast, east of Castlebay showing the difference in expression with variation in lithology. View looking east.

Fig. XVII-1

Fig. XVII-2

Fig. XVII-3

Fig. XVII-4. Joints striking at 40°. View looking east.
Shore north of Eoligarry pier.

Fig. XVII-5. Post-Lewisian dolerite dyke cutting foliated
gneiss. West of Halaman Bay.

Fig. XVII-4

Fig. XVII-5

Fig. XVIII-1. Equal area plot of 5250 poles to foliation, Barra. The average foliation dip is approximately 15^{o} towards 25^{o}. Contours at 1%, 2.5%, 5% and 7.5% intervals.

Fig. XVIII-2. Equal area plot of 1100 small fold axial plunges, Barra. The maximum plunges at approximately 10^{o} towards 100^{o}. Contours at 1%, 2%, 3%, 4%, 5% and 6%.

Fig. XVIII-3. Map to show the position of the grid west of the Heaval Thrust and the plots of data measured from the domains.

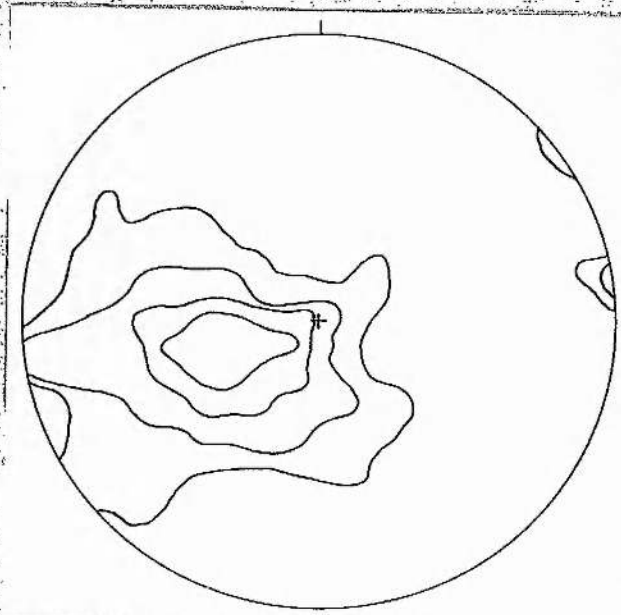


Fig. XVIII-1

Fig. XVIII-2

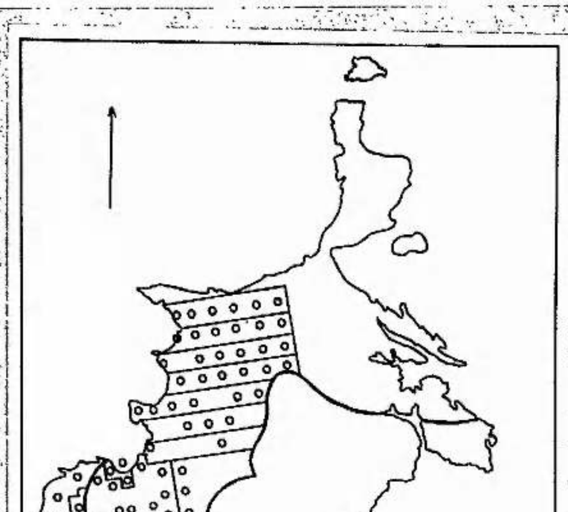


Fig. XVIII-3

Fig. XVIII-4. Diagram to show how small superimposed folds F_2 (a) compared with large folds F_2 (b) do not affect the overall attitude of the foliation.

Fig. XVIII-5. Equal area plot of 1350 poles to foliation east of (above) the Heaval Thrust. The average attitude of the foliation dips at approximately 40° towards 80°. Contours at 1%, 2.5%, 5%, 10%, 15% and 20% intervals.

Fig. XVIII-6. Simulated cross-folding to explain the form of figure 5. The large dots represent poles to foliation folded before folding about F_4. Rotation of 30° about F_4 causes spread of the poles to the positions marked by the dots surrounded by circles.

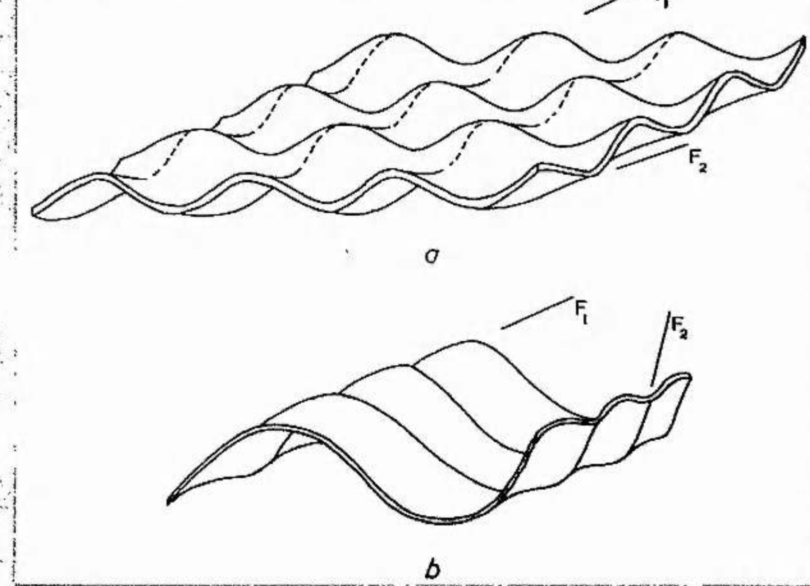


Fig. XVIII-4

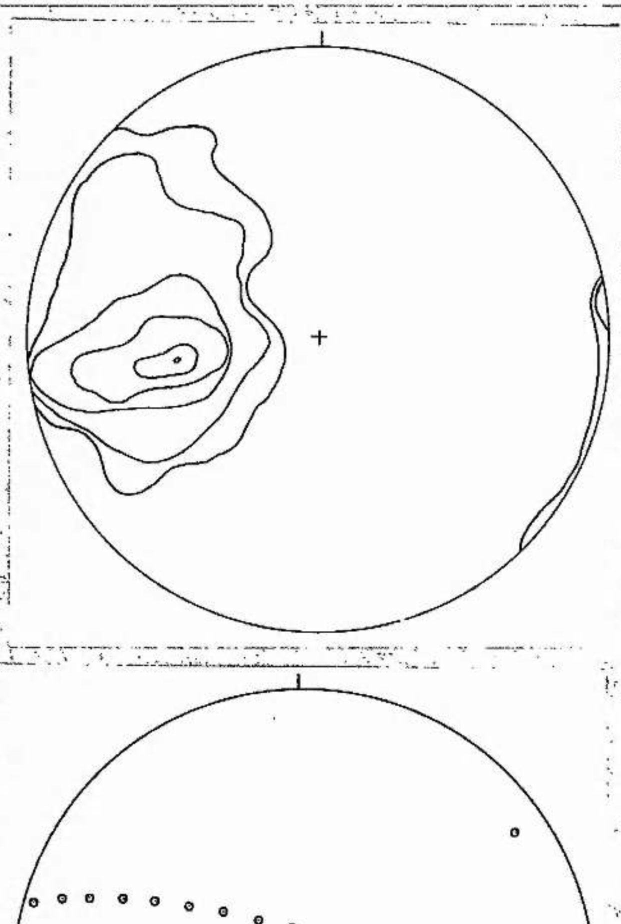


Fig. XVIII-5

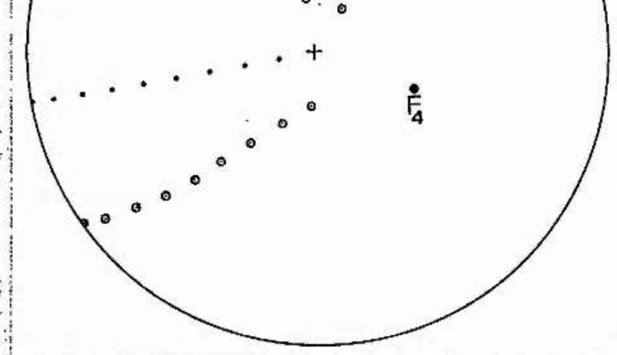


Fig. XVIII-6

Fig. XVIII-7. Equal area plot of 3060 poles to foliation west of (below) the Heaval Thrust. The maximum shows an average foliation dip of approximately 25° towards 60°. Contours at 1%, 2.5%, 5% and 10% intervals. The central area enclosed by the 10% contour varies from 10% to 15% density.

Fig. XVIII-8. Equal area plot of 1100 small fold axes in approximately the same relation to the foliation. They have been rotated about a vertical axis so that the strike of their associated foliation is "North". Most of the folds lying in the south-east quadrant belong to F_4. The clusters at "North" and "South" suggest that these folds were isoclinal with almost horizontal axes before folding on F_3. Otherwise there is no suggestion that a strong fold pattern was in existence prior to F_2.

Fig. XVIII-9. Equal area plot of all small fold axes tilted with levelling of F_4 (dots) and a diagram of their relative concentrations after rotation to the horizontal position about a level axis trending 100°. This shows groups corresponding to F_1 (30°) F_2 (165°) and F_3 (145°).

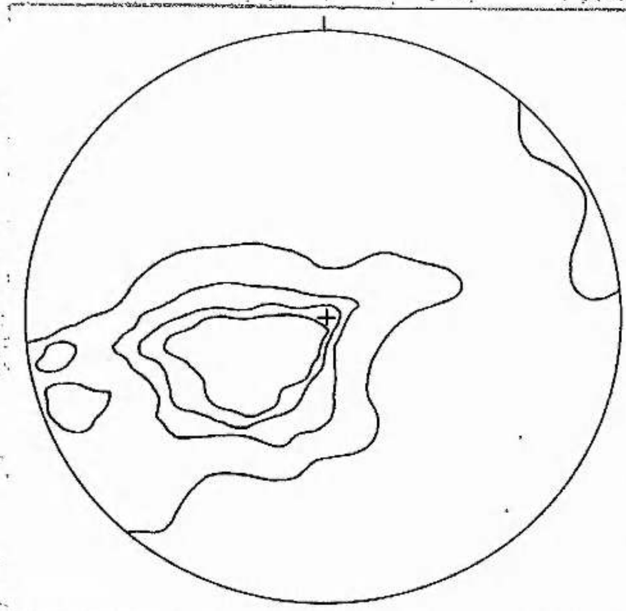


Fig. XVIII-7

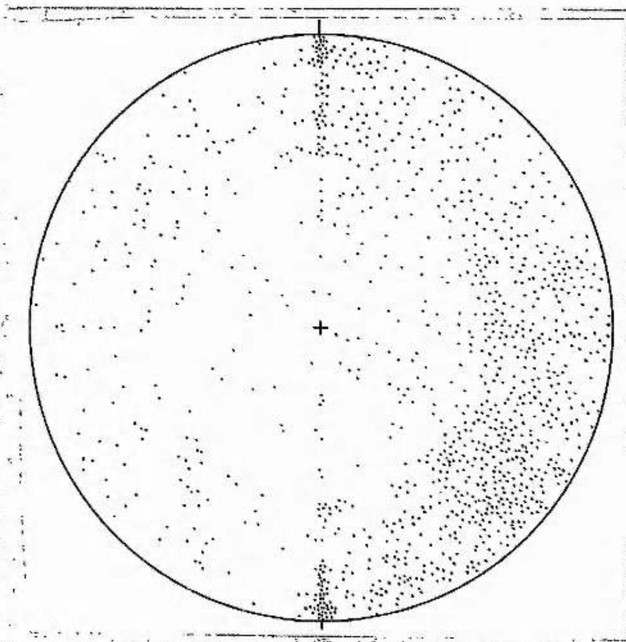


Fig. XVIII-8

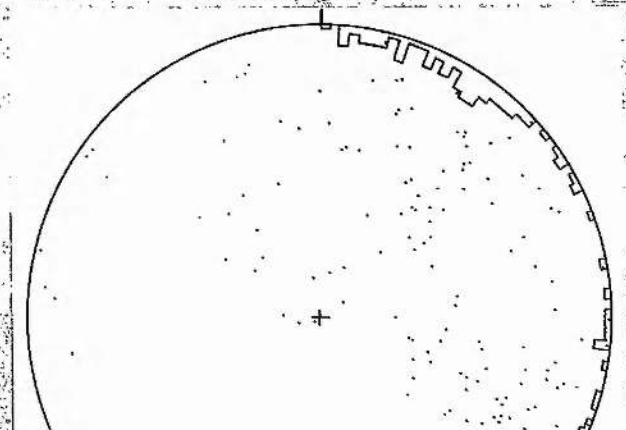


Fig. XVIII-9

Fig. XVIII-10. Equal area plot of 179 small fold axes east of (above) the Thrust. Maxima plunge at 60° towards 20°, 35° towards 30° and 40° towards 120°. Contours at 1%, 2.5%, 5% and 7% drawn by free counter method.

Fig. XVIII-11. Equal area plot of 920 small fold axes west of (below) the Thrust. Maxima plunge at 25° towards 10° and 10° towards 100°. Contours separate areas of 0.5%, 1%, 2%, 3%, 4%, 5%, 6% and 7% density.

Fig. XVIII-12. A plot of strikes of vertical foliation measured east of (above) the Thrust.

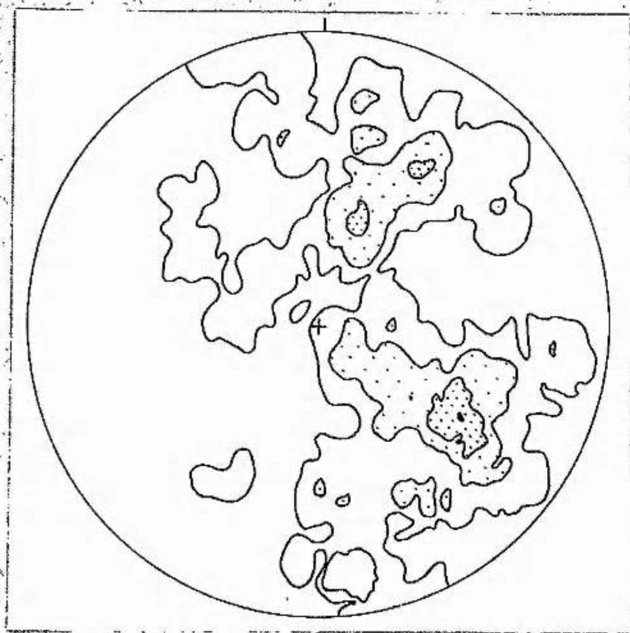


Fig. XVIII-10

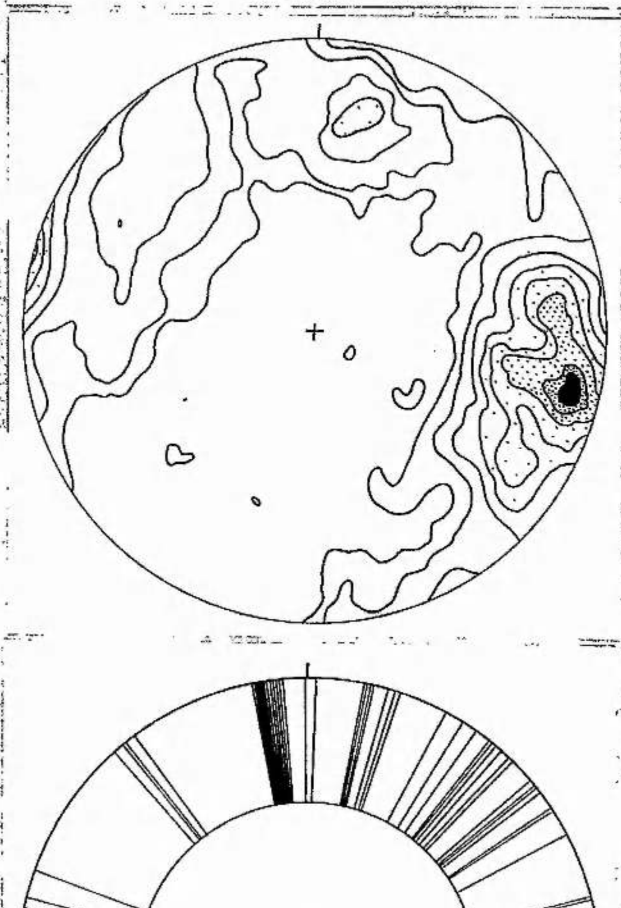


Fig. XVIII-11

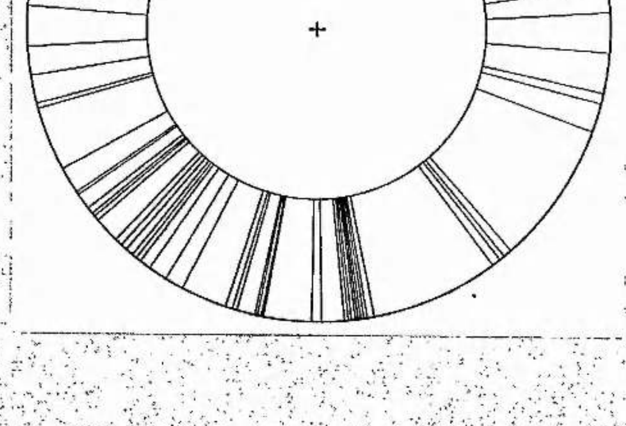


Fig. XVIII-12

Fig. XVIII-13. Plot of strikes of vertical foliation measured west of (below) the Thrust.

Fig. XVIII-14. Plot of strikes of all vertical foliation recorded, Barra.

Fig. XVIII-15. Equal area plot of 630 S-poles to foliation and the trace of the foliation surface (dashed) dipping at 16^{o} towards 65^{o} defined by the plot. Borve to Cuier. Contours at 1%, 2.5%, 5%, 10% and 15% intervals.

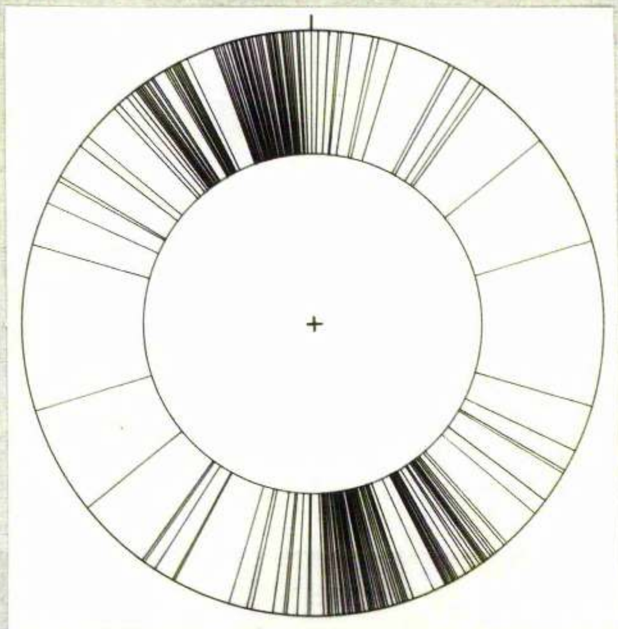


Fig. XVIII-13

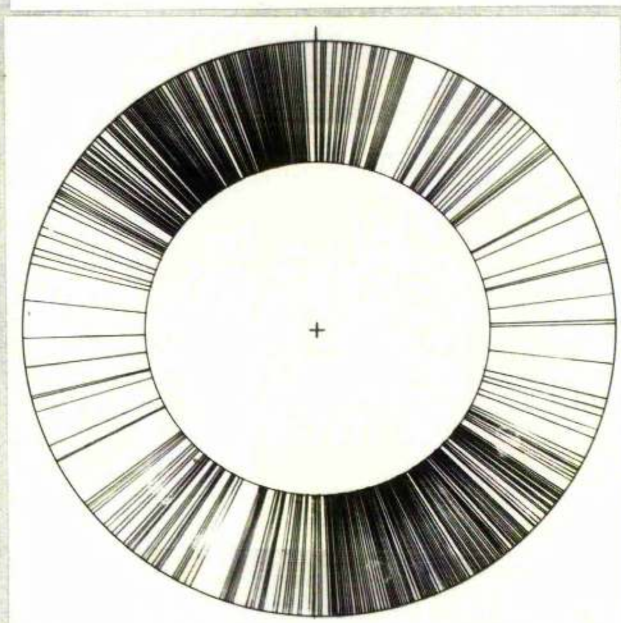


Fig. XVIII-14

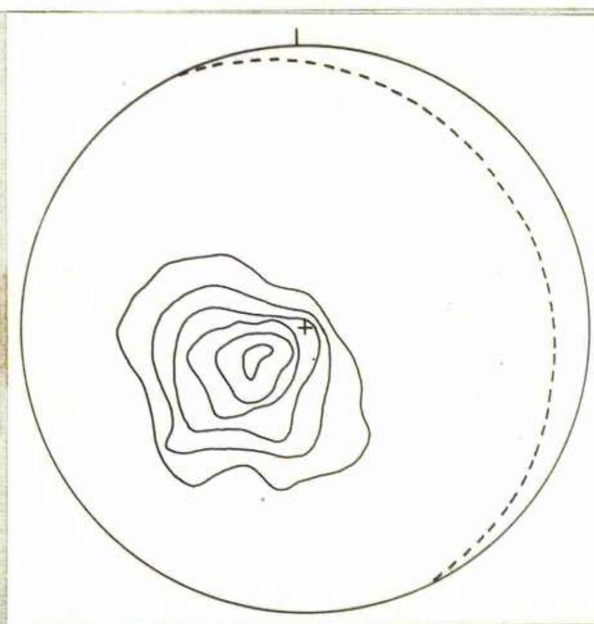


Fig. XVIII-15

Fig. XVIII-16. Synoptic diagram of π S-pole girdles, β-diagram of average foliation surfaces (solid lines) and overall average foliation surface (dashed) from the plot of figure XVIII-15. Borve to Cuier.

Fig. XVIII-17. Equal area plot of 20 S-poles. Domain I. Borve to Cuier. π is the pole to the girdle through the plot. Contours at 5%, 10% and 15% intervals.

Fig. XVIII-18. Equal area plot of 45 S-poles. Domain II. Borve to Cuier. π is the pole to the girdle through the plot. Contours at 2.5%, 5%, 10%, 15% and 20% intervals.

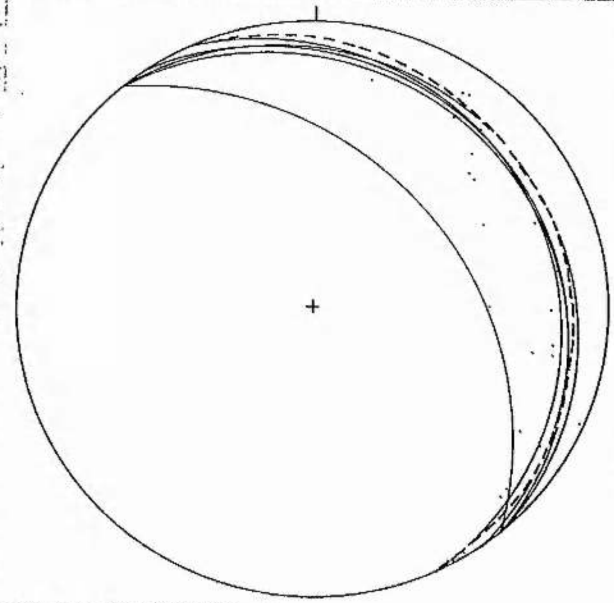


Fig. XVIII-16

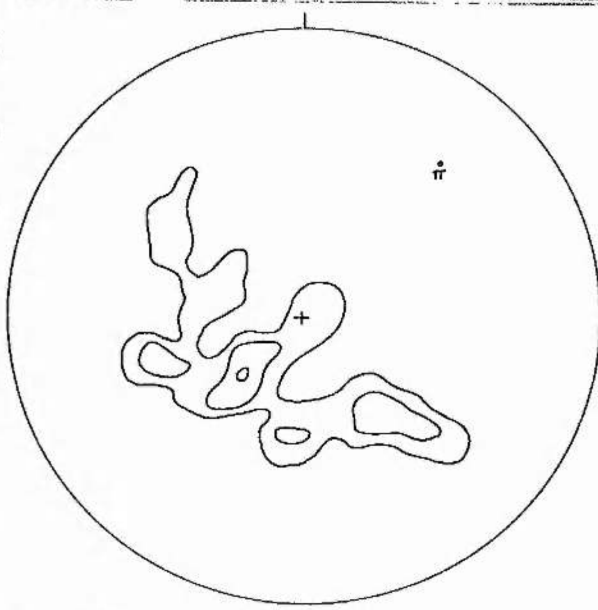


Fig. XVIII-17

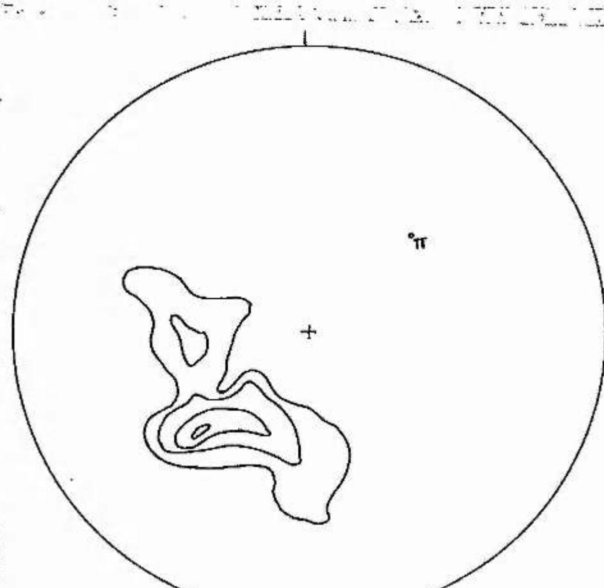


Fig. XVIII-18

Fig. XVIII-19. Equal area plot of 108 S-poles. Domain III. Borve to Cuier. Contours at 2.5%, 5%, 10% and 12.5% intervals.

Fig. XVIII-20. Equal area plot of 144 S-poles. Domain IV. Borve to Cuier. Contours at 2.5%, 5%,10%, 15% 20% and 25% intervals.

Fig. XVIII-21. Equal area plot of 98 S-poles. Domain V. Borve to Cuier. Contours at 2.5%, 5%, 10%, 15% and 20% intervals.

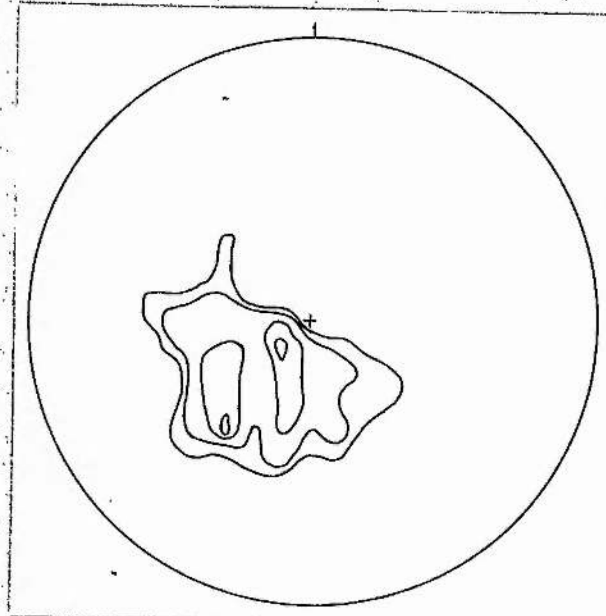


Fig. XVIII-19

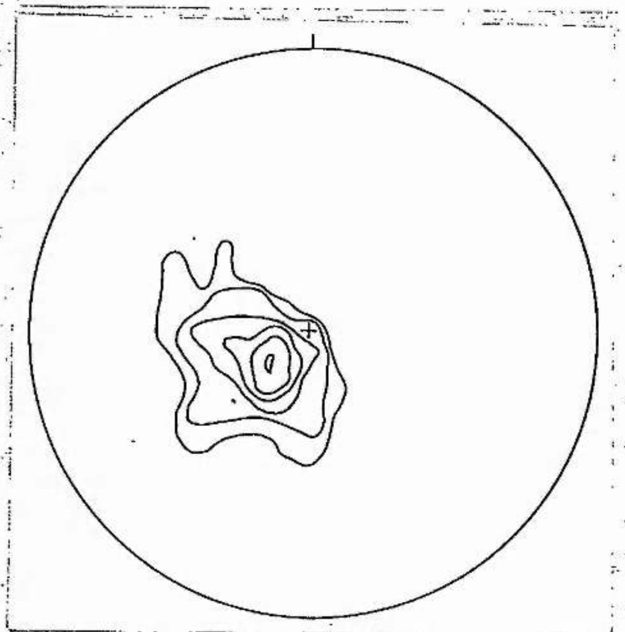


Fig. XVIII-20

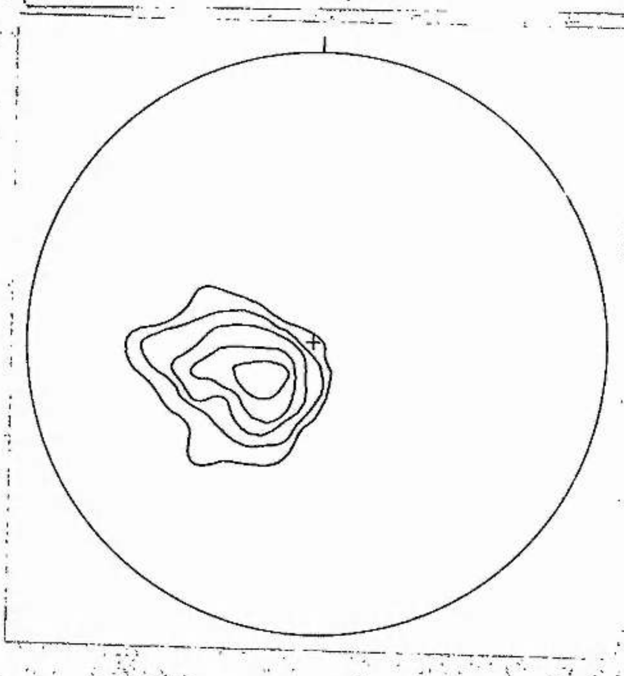


Fig. XVIII-21

Fig. XVIII-22. Equal area plot of 88 S-poles. Domain VI. Borve to Cuier. Contours at 2.5%, 5%, 10%, 15%, 20%, 25% and 30% intervals.

Fig. XVIII-23. Equal area plot of 120 S-poles. Domain VII. Borve to Cuier. Contours at 2.5%, 5%, 10%, 15%, 20%, 30% and 35% intervals.

Fig. XVIII-24. Synoptic β-diagram from S-poles maxima girdles and average foliation attitude for the area. Note that the spread of points suggests some dispersion about F_4. Borve to Cuier.

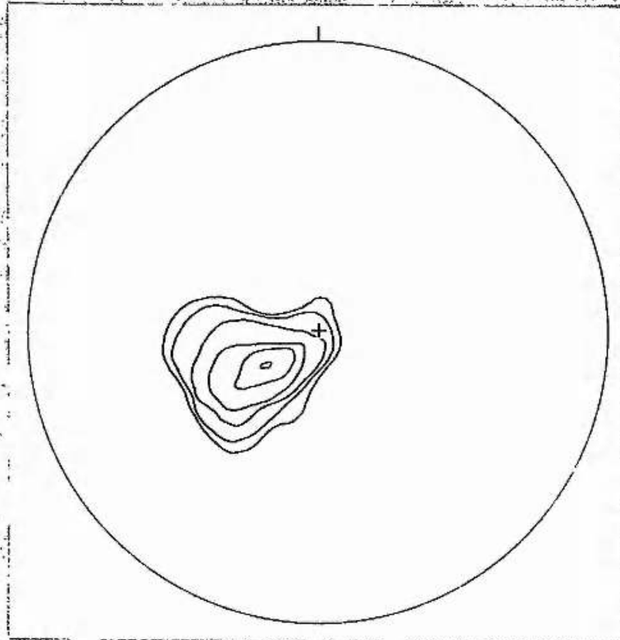


Fig. XVIII-22

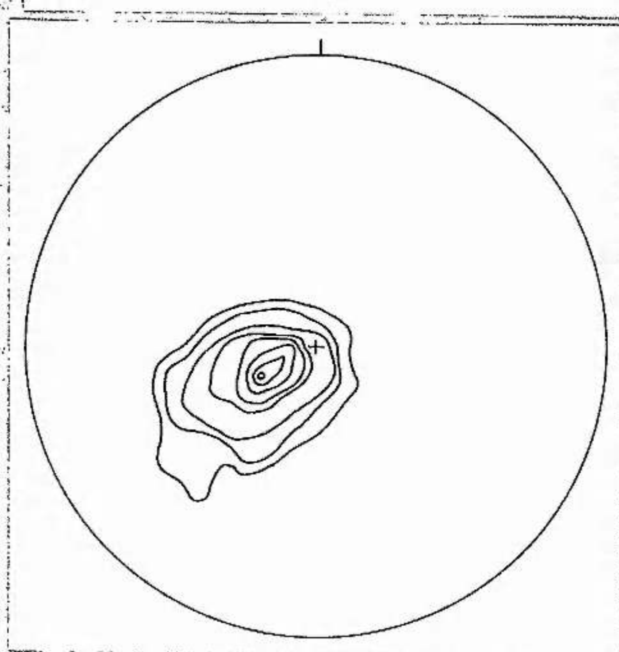


Fig. XVIII-23

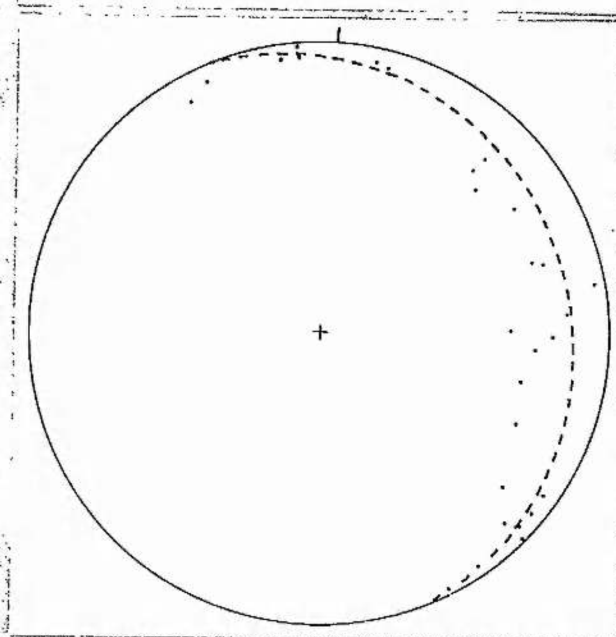


Fig. XVIII-24

Fig. XVIII-25. β-diagram of foliation, measured at Beinn Mhartuin. The average intersection plunges at approximately 40° towards 54° and therefore defines an F_5 fold.

Fig. XVIII-26. Equal area plot of 60 small fold axes. Borve to Cuier. Contoured by the Mellis method. Densities of 1%, 2.5%, 5%, 7.5%, 8% and 10%.

Fig. XVIII-27. Equal area plot of 965 S-poles to foliation Castlebay to Halaman Bay. Contours at 1%, 2.5%, 5%, 7.5% and 10% intervals.

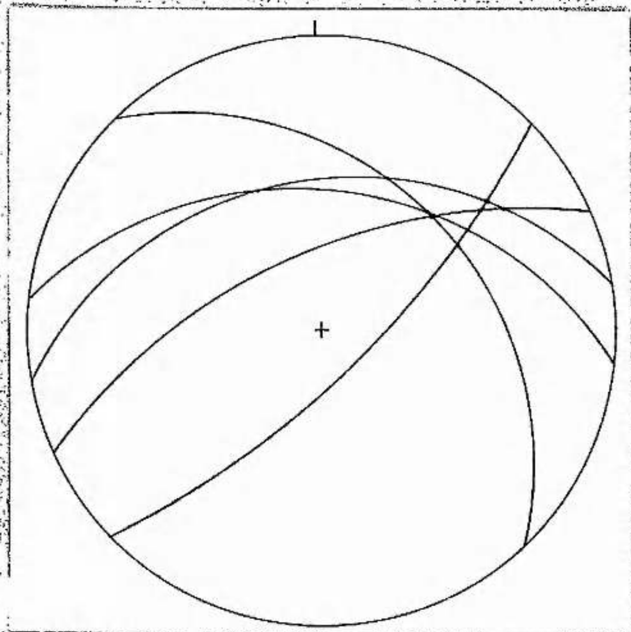


Fig. XVIII-25

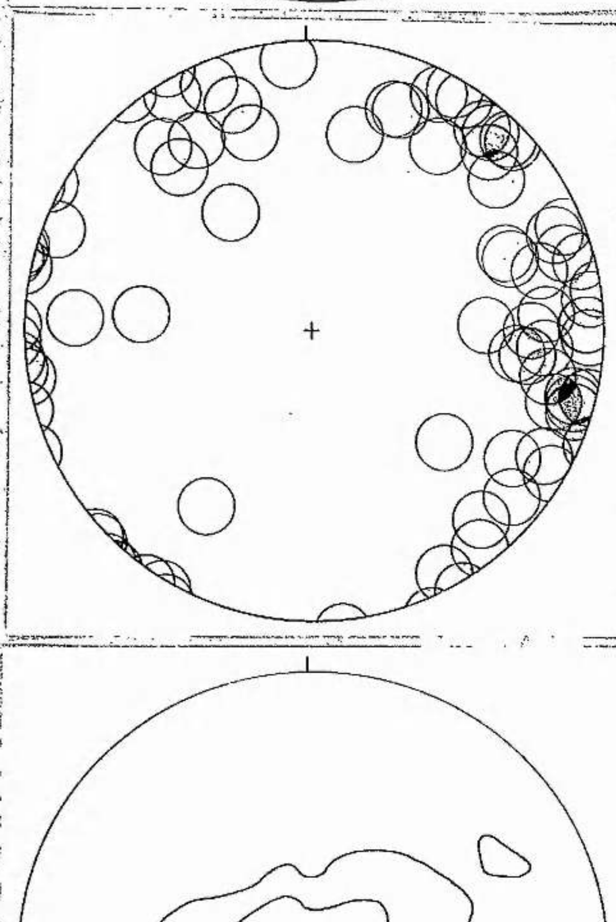


Fig. XVIII-26

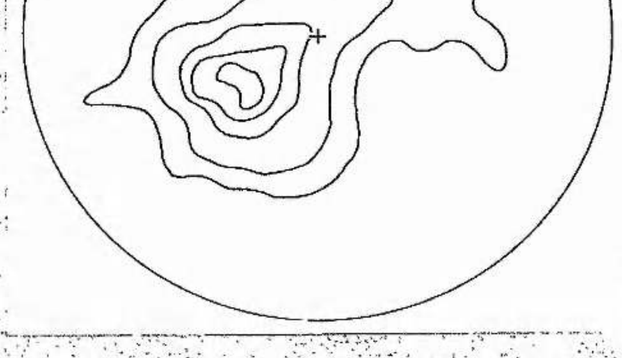


Fig. XVIII-27

Fig. XVIII-28. Equal area plot of 60 S-poles, the average attitude of the foliation (dashed line) and 6 small fold axes (dots) from Domain I, Castlebay to Halaman Bay. Contours at 5%, 10%, 15% and 20% intervals.

Fig. XVIII-29. Equal area plot of 130 S-poles, the average attitude of the foliation (dashed line) and 73 small fold axes (dots) from Domain II, Castlebay to Halaman Bay. Contours at 2.5%, 5%, 10%, 15% and 20% intervals.

Fig. XVIII-30. Equal area plot of 100 S-poles, the average attitude of the foliation (dashed line) and 120 small fold axes (dots) from Domain III, Castlebay to Halaman Bay. Contours at 5%, 10%, 15%, 20% and 25% intervals.

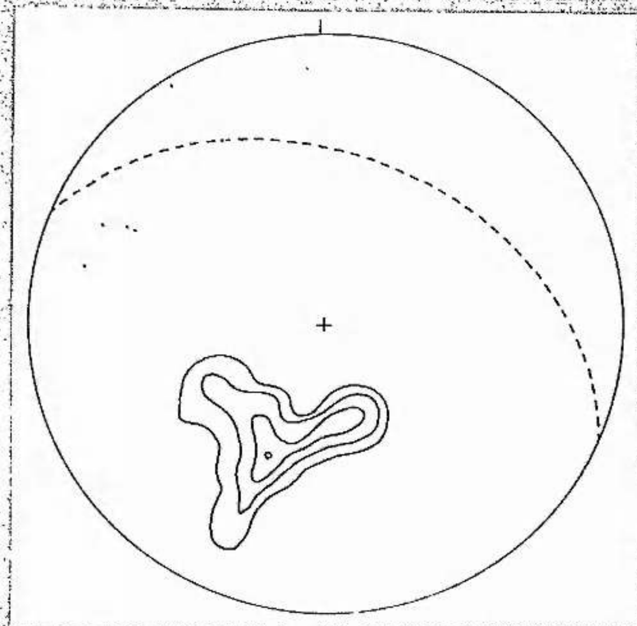


Fig. XVIII-28

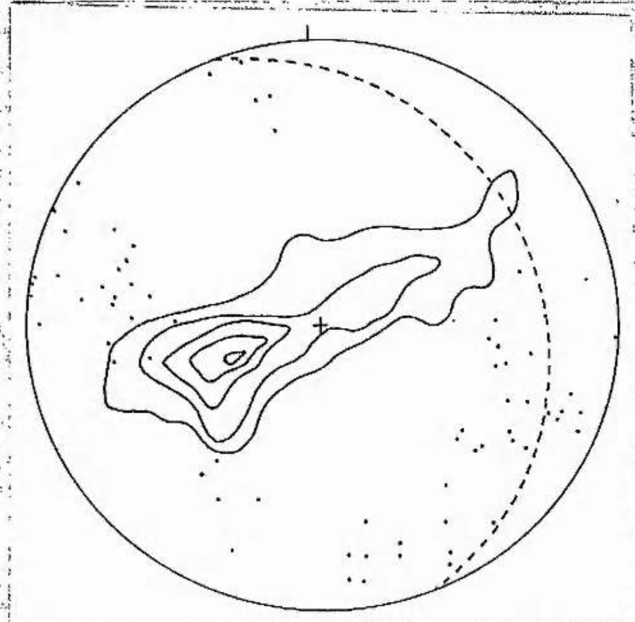


Fig. XVIII-29

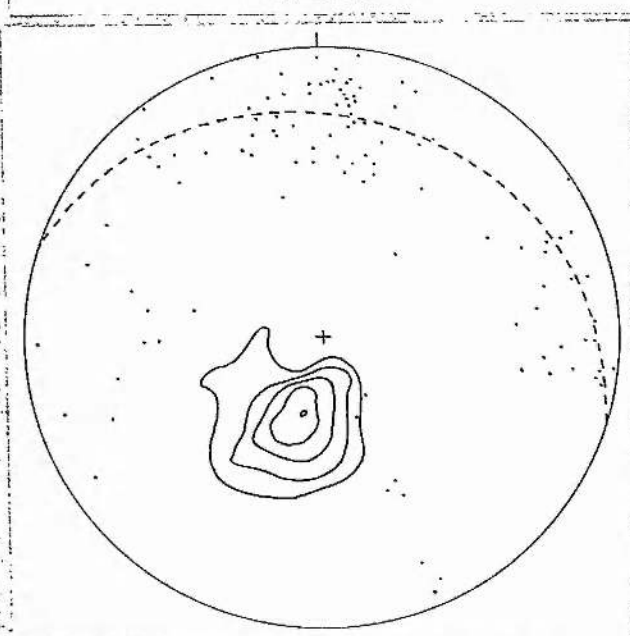


Fig. XVIII-30

Fig. XVIII-31. Equal area plot of 115 S-poles, the average attitude of the foliation (dashed line) and 57 small fold axes (dots) from Domain IV, Castlebay to Halaman Bay. Contours at 5%, 10%, 15%, 20% and 25% intervals.

Fig. XVIII-32. Equal area plot of 270 S-poles, the average attitude of the foliation (dashed line) and 58 small fold axes (dots) from Domain VI, Castlebay to Halaman Bay. Contours at 2.5%, 5%, 10% and 15% intervals.

Fig. XVIII-33. Equal area plot of 70 S-poles, the average attitudes of the foliation (dashed lines) and 6 small fold axes (dots) from Domain V, Castlebay to Halaman Bay. Contours at 2.5%, 5%, 7.5% and 10% intervals.

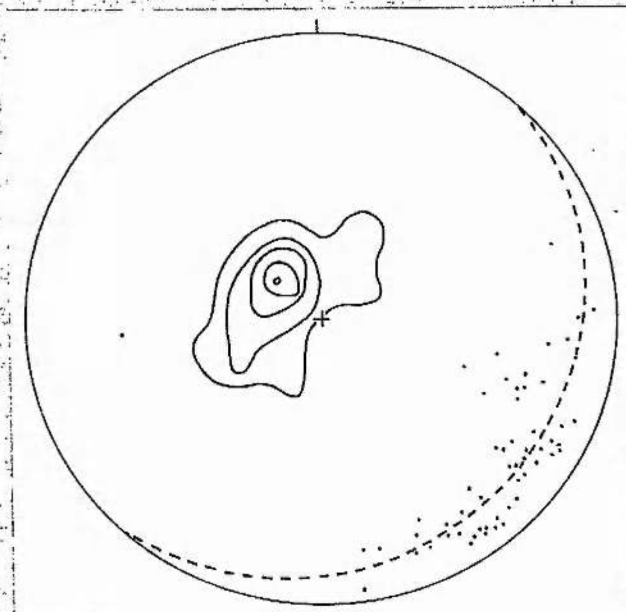


Fig. XVIII-31

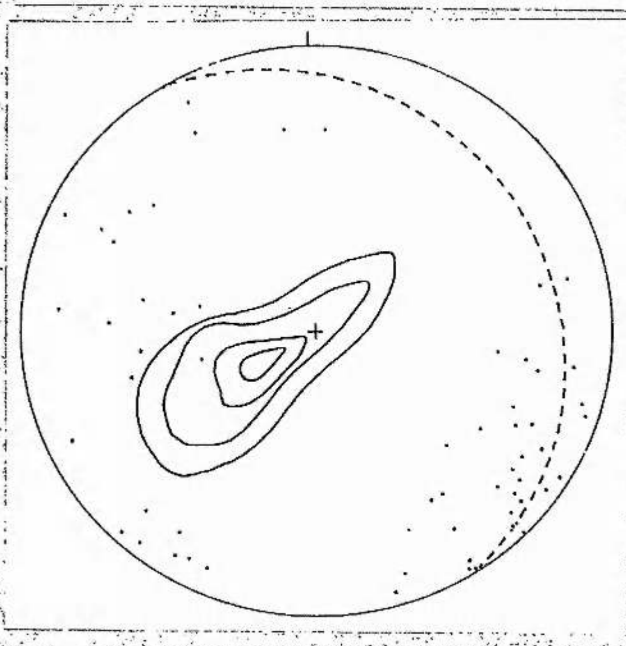


Fig. XVIII-32

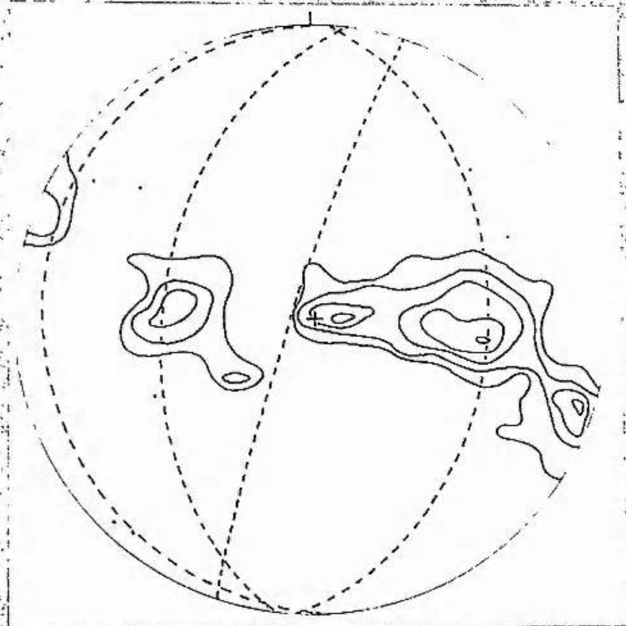


Fig. XVIII-33

Fig. XVIII-34. Equal area plot of 320 small fold axes. Castlebay to Halaman Bay. Contours at 1%, 2.5% and 5% intervals.

Fig. XVIII-35. Equal area plot of 222 S-poles to foliation west of the Tangaval Thrust. Contours at 1%, 2.5%, 5%, 10% and 15% intervals.

Fig. XVIII-36. Equal area plot of 122 S-poles to foliation on the south-east plunging structure, west of the Tangaval Thrust. Contours at 5%, 10%, 15% and 20% intervals.

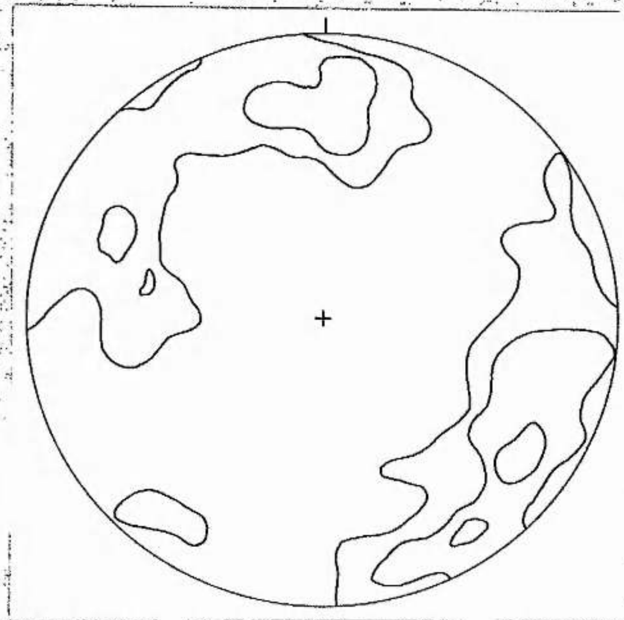


Fig. XVIII-34

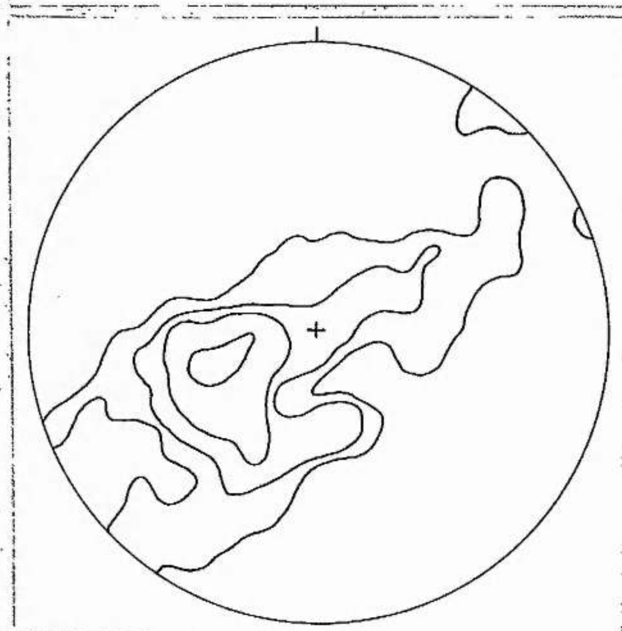


Fig. XVIII-35

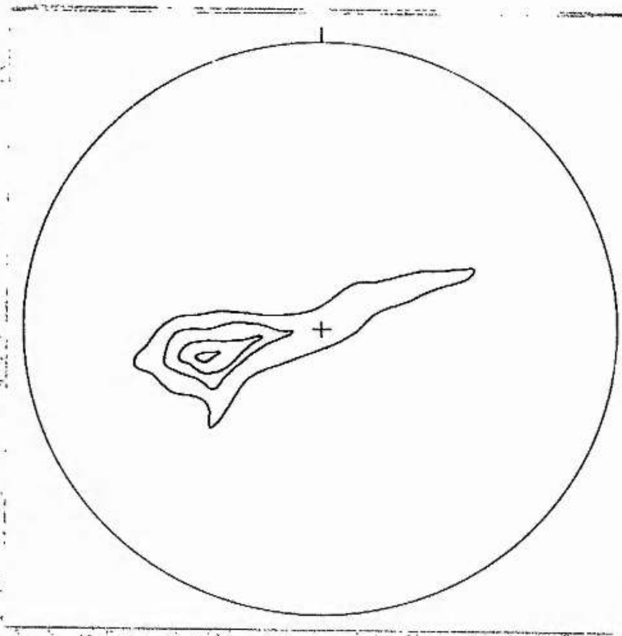


Fig. XVIII-36

Fig. XVIII-37. Equal area plot of 128 S-poles to foliation on the north-east plunging structure, west of the Tangaval Thrust. Contours at 2.5%, 5%, 7.5%, 10% and 12.5% intervals.

Fig. XVIII-38. Equal area plot of 84 S-poles on the north-west plunging structure lying between the two Thrusts. Contours at 1%, 2.5%, 5% and 7.5% intervals.

Fig. XVIII-39. Equal area plot of small fold axes and 364 S-poles on the south-east plunging structure lying between the Thrusts. Castlebay to Halaman Bay. Contours at 2.5%, 5%, 7.5%, 10% and 12.5% intervals.

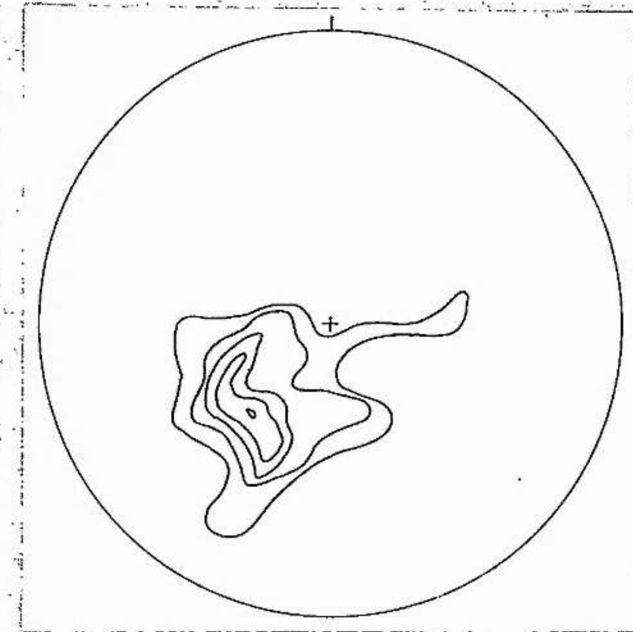


Fig. XVIII-37

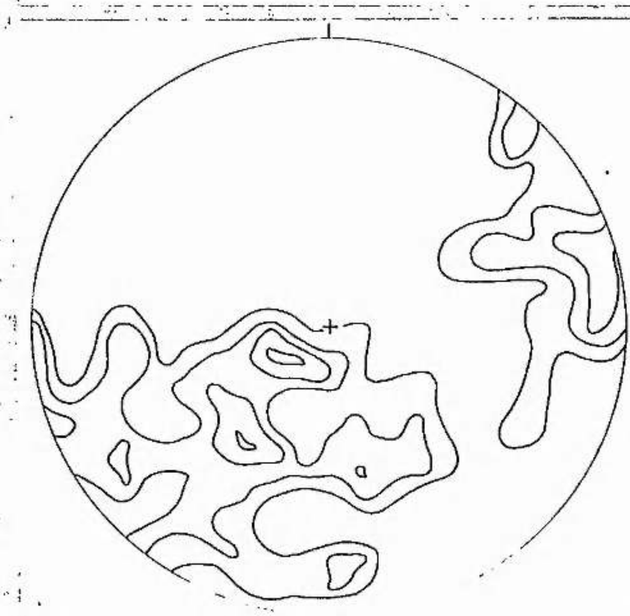


Fig. XVIII-38

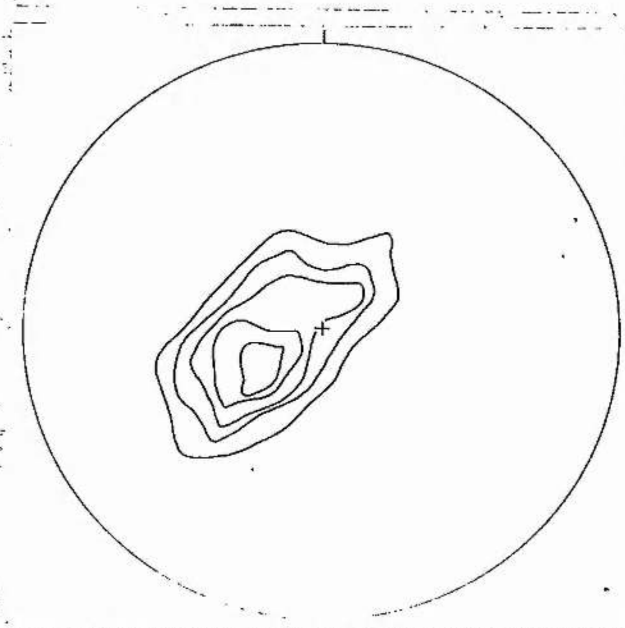


Fig. XVIII-39

Fig. XVIII-40. Equal area plot of 130 small fold axes between the two Thrusts Castlebay to Halaman Bay. Contours at 2.5%, 5%, 7.5%, 10% and 12.5% intervals.

Fig. XVIII-41. Diagram of a surface constructed from the equal area plot of folded folds of figure XVIII-40. Plots of folds in this surface resulting from folding about F_3, F_4 and F_5 axes characteristically form hysteresis type curves.

Fig. XVIII-42. Synoptic diagram of β-maxima from average attitudes of the foliation (S) of plots from Castlebay to Halaman Bay. The concentrations close to North and South probably represent early isoclinal folds and F_2 axes and the scatter from south-east to east-north-east, folds of F_3 and F_4 generation.

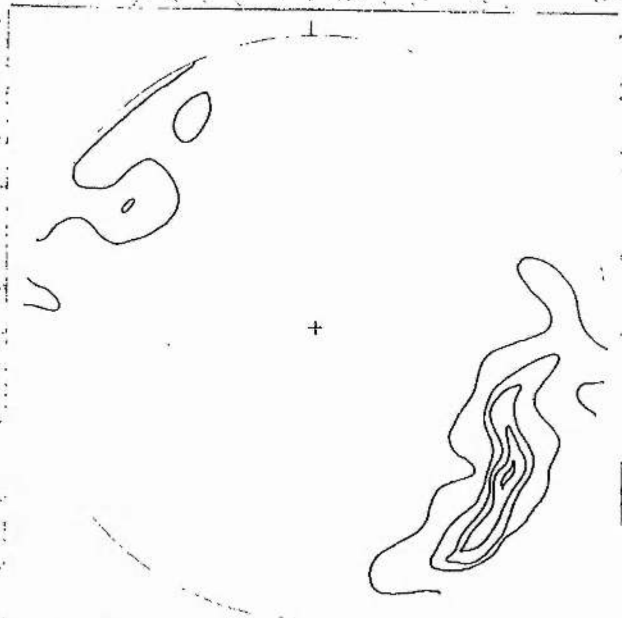


Fig. XVIII-40

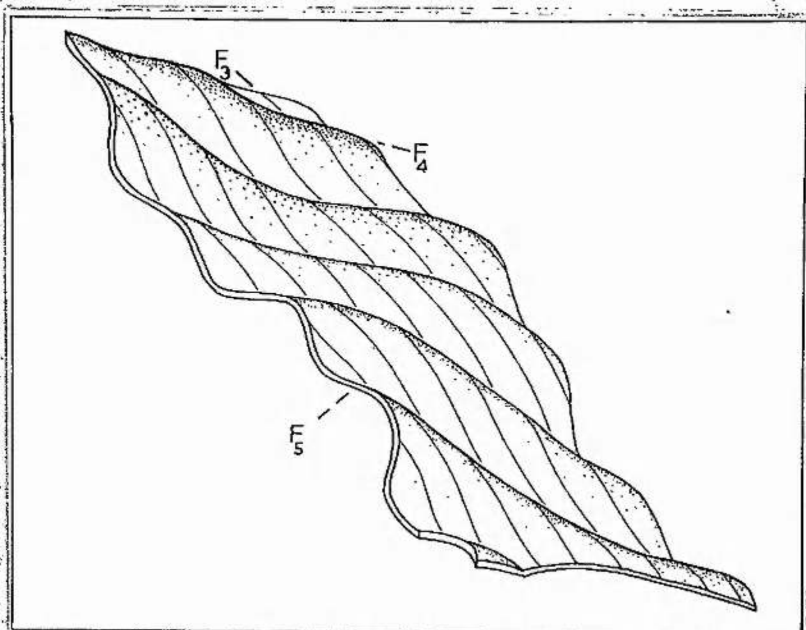


Fig. XVIII-41

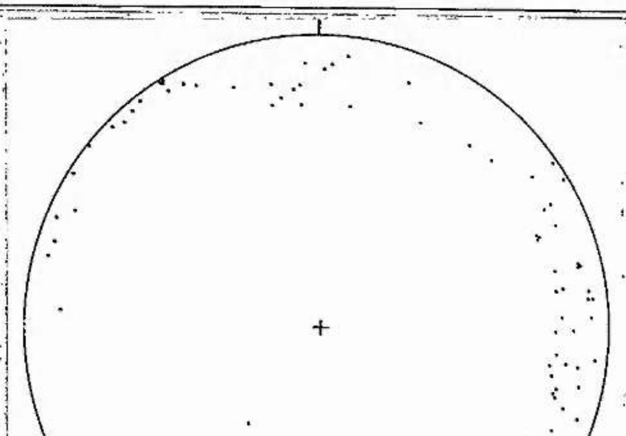


Fig. XVIII-42

Fig. XVIII-43. Synoptic diagram of π S-pole girdles from the sub-areas between Castlebay and Halaman Bay.

Fig. XVIII-44. Equal area plot of 264 S-poles and 46 small fold axes (dots) from the Croig. Contours at 5%, 7.5%, 10%, 15%, 20% and 25% intervals. Subdivision of the area and plotting of the data on four separate plots showed the influence of F_3, F_4 and F_5 folding on the patterns obtained.

Fig. XVIII-45. Equal area plot of 132 S-poles and the average foliation attitude (dashed line) from Rudha Glas. Contours at 5%, 10%, 15%, 20% and 25% intervals.

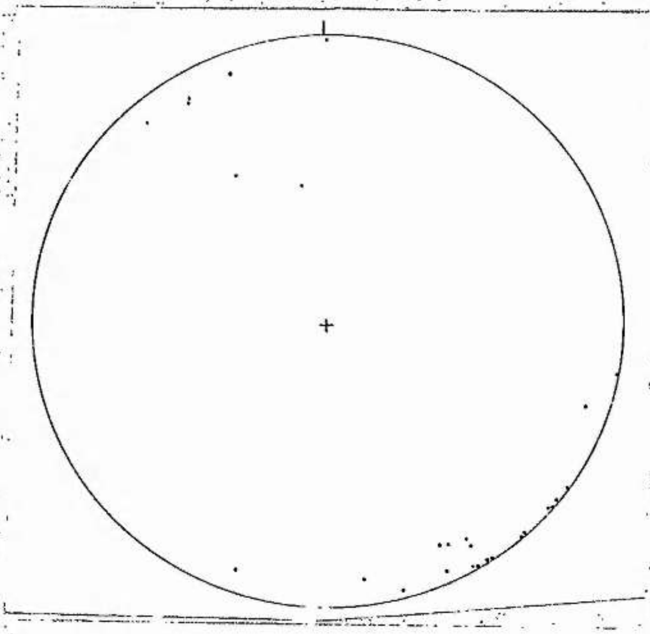


Fig. XVIII-43

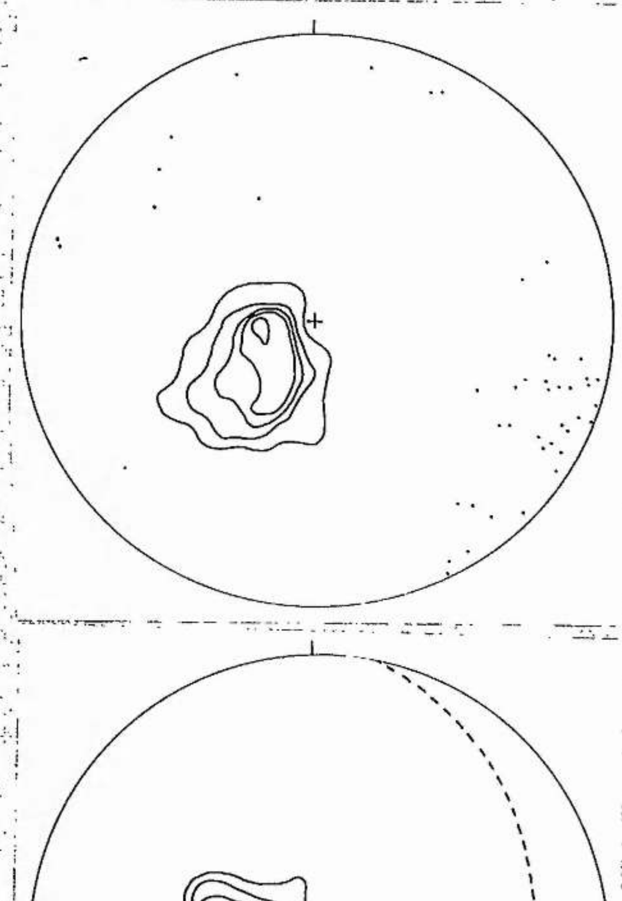


Fig. XVIII-44

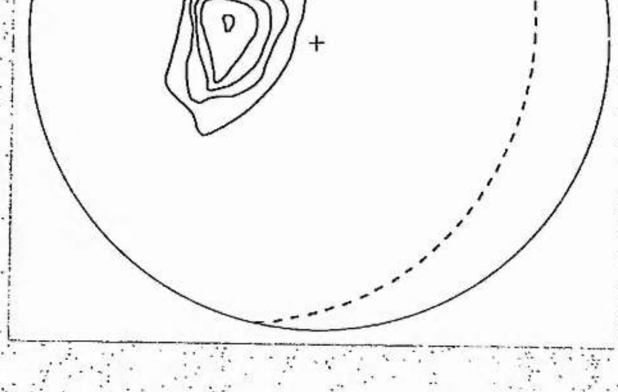


Fig. XVIII-45

Fig. XVIII-46. Equal area plot of small fold axes from Nask.

Fig. XVIII-47. Comparison of characteristic fold styles representing each phase from isoclinal folds (F_0, early isoclinal) to F_5.

Fig. XVIII-48. Equal area plot of small fold axes and poles to foliation (dots). The average foliation attitude is represented by a circled dot. Solid circles are larger, more open folds, and open circles are smaller, tighter folds. Exposure I, south of Nagh nan Clach.

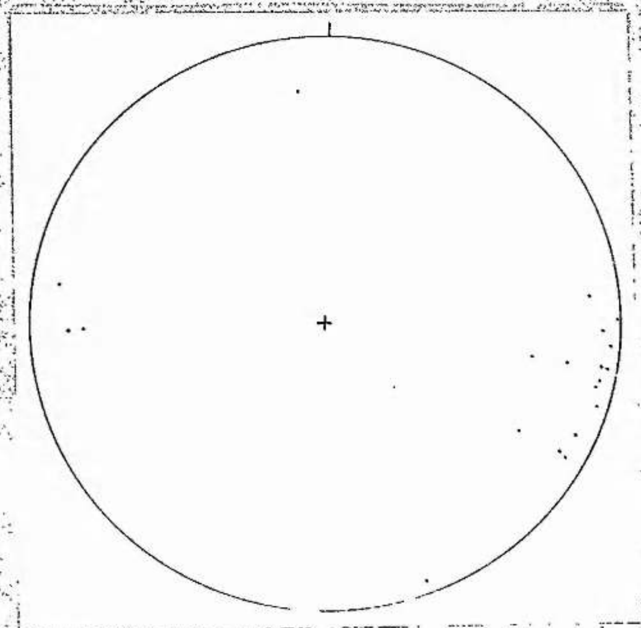


Fig. XVIII-46

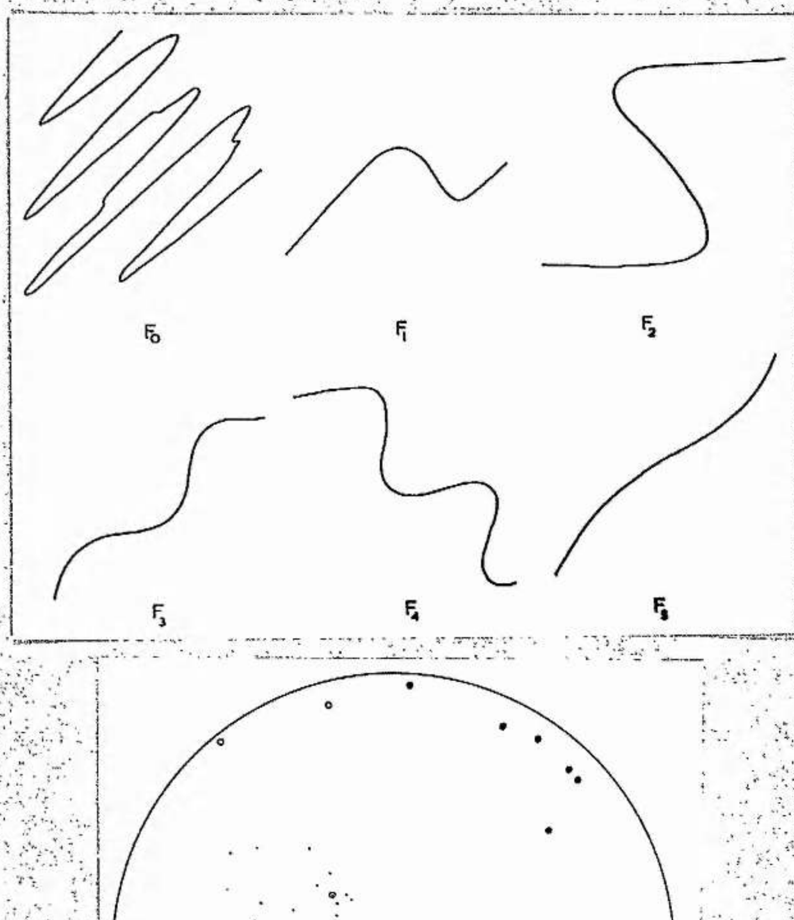


Fig. XVIII-47

Fig. XVIII-48

Fig. XVIII-49. Equal area plot of small fold axes (large dots) and poles to foliation (small dots). The average foliation attitude is represented by a circled dot. Exposure II, south of Bagh nan Clach.

Fig. XVIII-50. Equal area plot of small fold axes and poles to foliation (dots). The average foliation attitude is represented by the encircled dot. Exposure III. Coast south of Bagh nan Clach.

Fig. XVIII-51. Equal area plot of small fold axes. The pole of the average attitude of the foliation is represented by the circled dot. Bagh nan Clach.

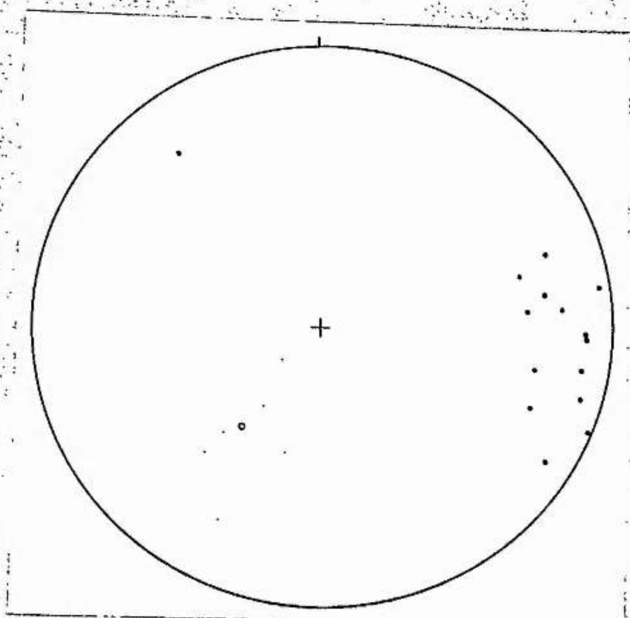


Fig. XVIII-49

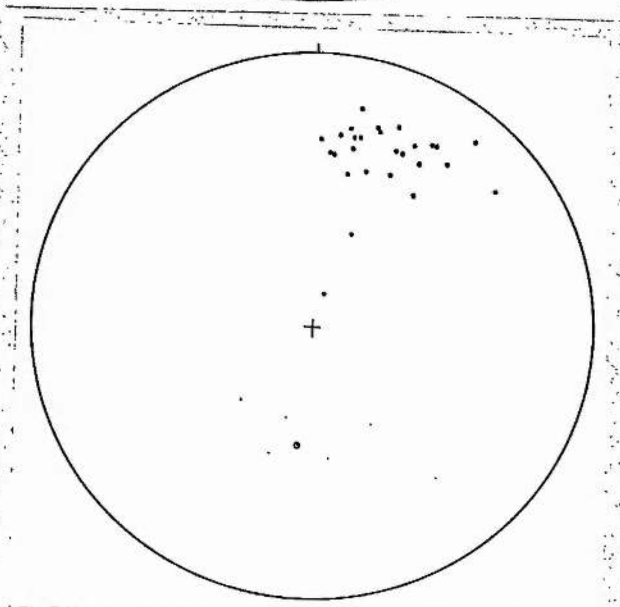


Fig. XVIII-50

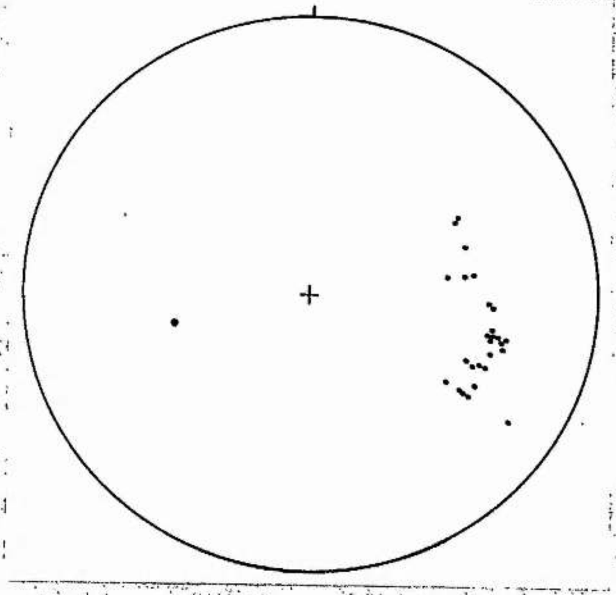


Fig. XVIII-51

Fig. XVIII-52. Equal area plot of small fold axes. The pole of the average attitude of the foliation is represented by the circled dot. Coast south of Doirlinn Head.

Fig. XVIII-53. Equal area plot of small fold axes and poles to foliation (small dots). The average foliation pole is represented by the circled dot. Exposure I. Hillside north of Castlebay Secondary School.

Fig. XVIII-54. Equal area plot of small fold axes and poles to foliation (small dots). The average foliation pole is represented by the circled dot. Exposure II. Hillside north of Castlebay Secondary School.

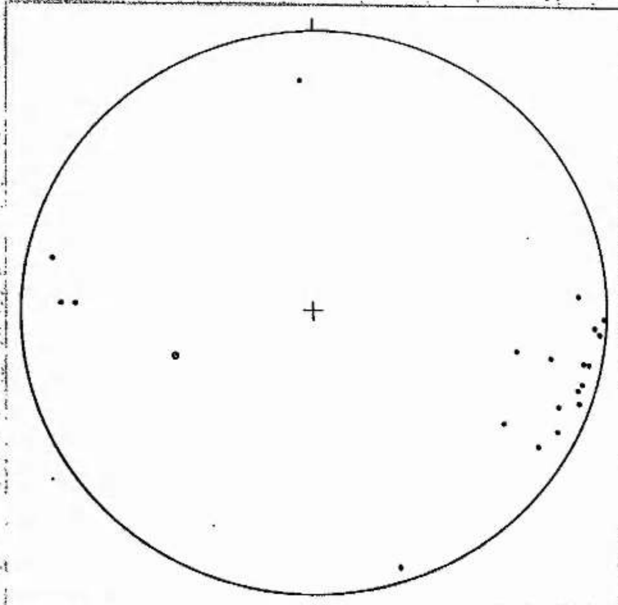


Fig. XVIII-52

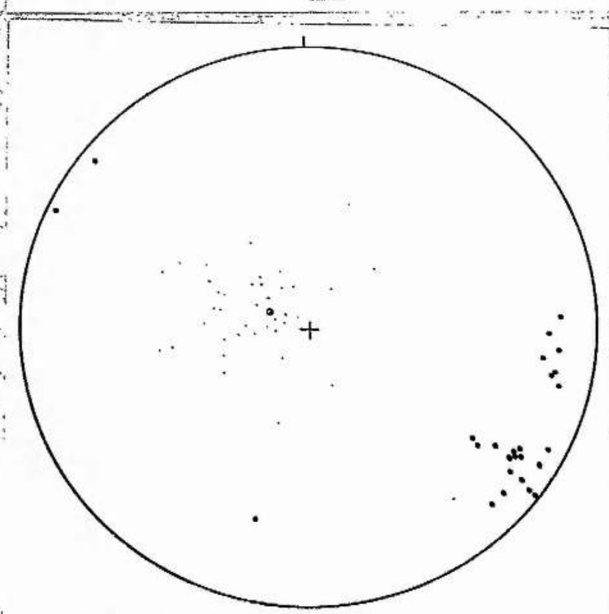


Fig. XVIII-53

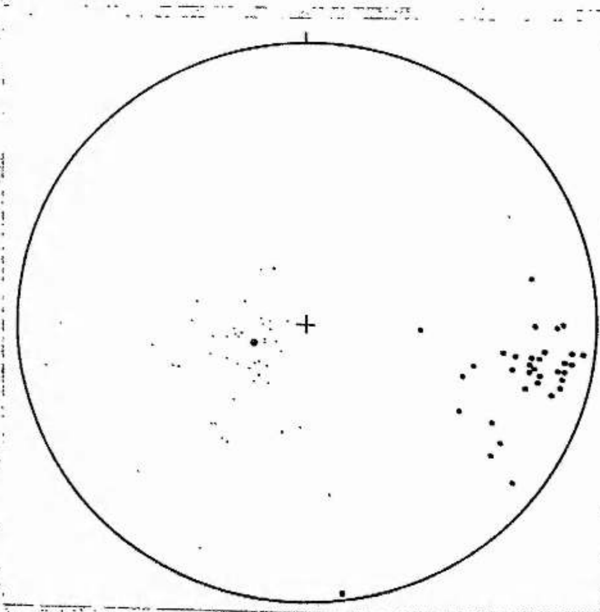


Fig. XVIII-54

Fig. XVIII-55. Equal area plot of small fold axes and poles to foliation (small dots). The average foliation pole is represented by the circled dot. Exposure III. Hillside north of Castlebay Secondary School.

Fig. XVIII-56. Equal area plot of small fold attitudes. The pole of the average fold attitude is represented by the circled dot. Shore east of Ersary.

Fig. XVIII-57. Equal area plot of small fold attitudes. The pole of the average fold attitude is represented by the circled dot. South-west flank of Beinn Mhartuin.

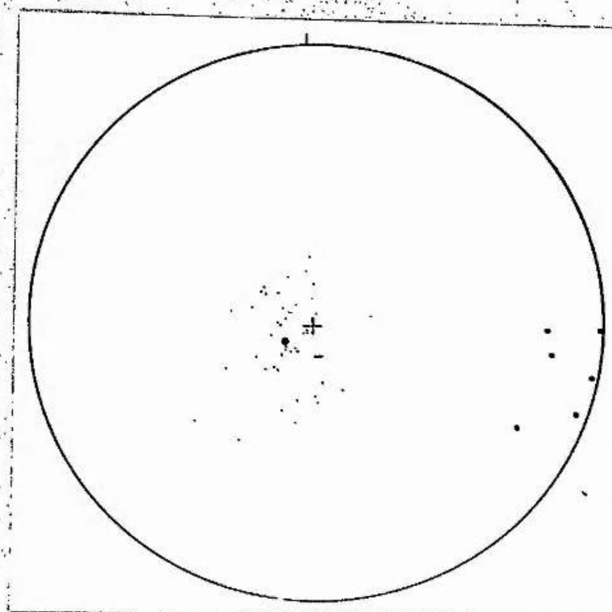


Fig. XVIII-55

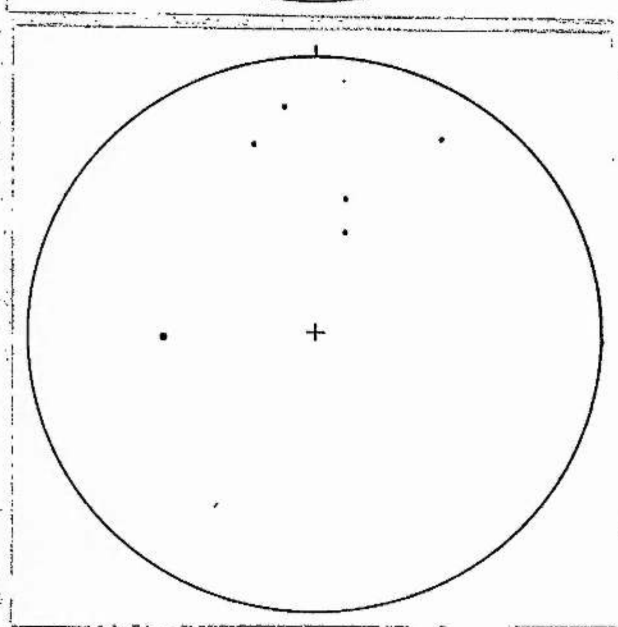


Fig. XVIII-56

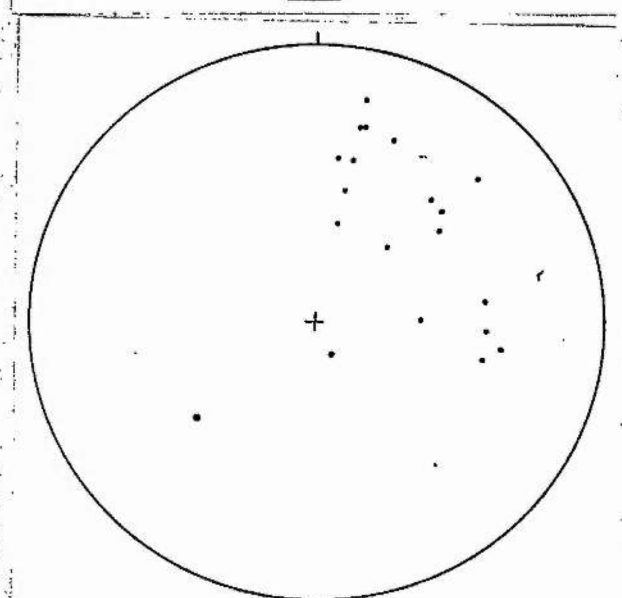


Fig. XVIII-57

Fig. XVIII-58. Equal area plot of small fold axes (large dots and circles) and poles to foliation (small dots). Large open folds are shown as large solid circles and smaller tight folds as open circles. The pole of the average foliation attitude is represented by a circled dot. Halaman skerry.

Fig. XVIII-59. Equal area plot of the attitudes of small fold axes. The pole of the average attitude of the foliation is represented by a circled dot. Exposure I. West end of Halaman Bay.

Fig. XVIII-60. Equal area plot of the attitudes of small fold axes. The pole of the average attitude of the foliation is represented by a circled dot. Exposure II. West end of Halaman Bay.

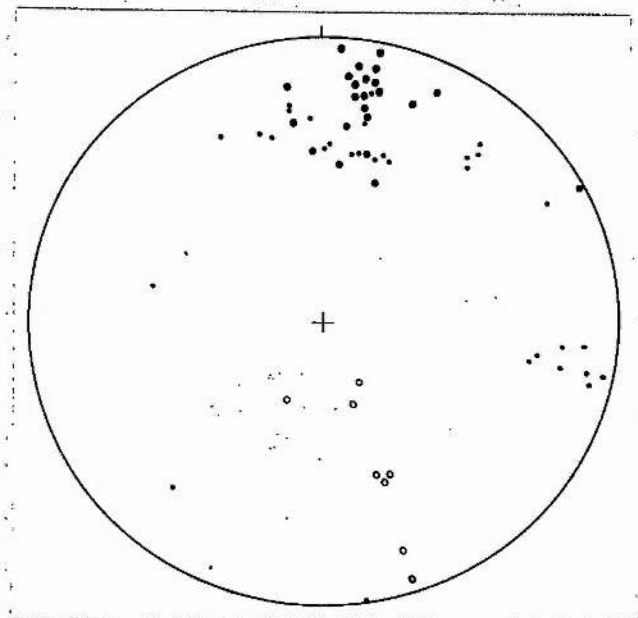


Fig. XVIII-58

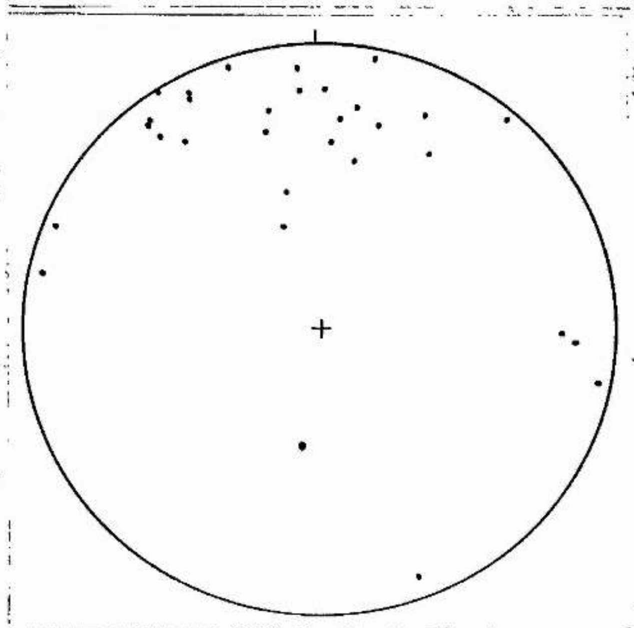


Fig. XVIII-59

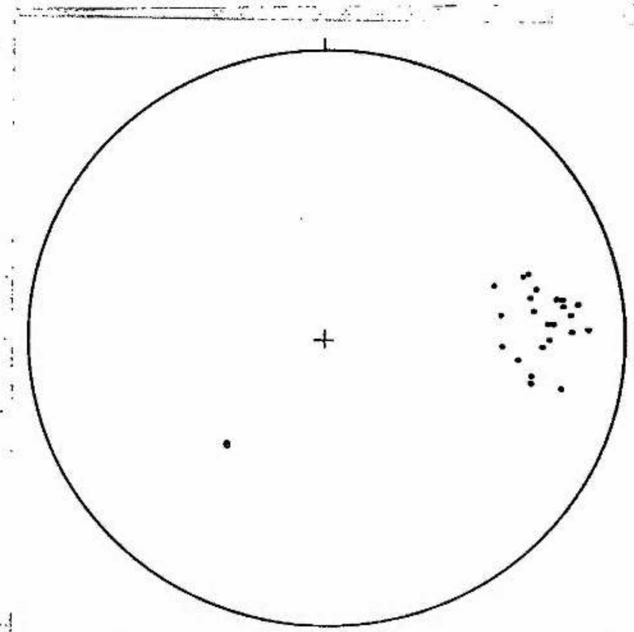


Fig. XVIII-60

Fig. XVIII-61. Equal area plot of the attitudes of small fold axes. The pole of the average attitudes of the foliation is represented by circled dots. Exposure I. Coast between Ard na Gregaid and Halaman Bay.

Fig. XVIII-62. Equal area plot of the attitudes of small fold axes. The pole of the average attitude of the foliation is represented by a circled dot. Exposure II. Coast between Ard na Gregaid and Halaman Bay.

Fig. XVIII-63. Synoptic diagram of approximate averages of groups of folds from all plots in relation to the average foliation attitude for Barra (circled dot represents pole). Solid circles represent strong concentrations and open circles diffuse groups.

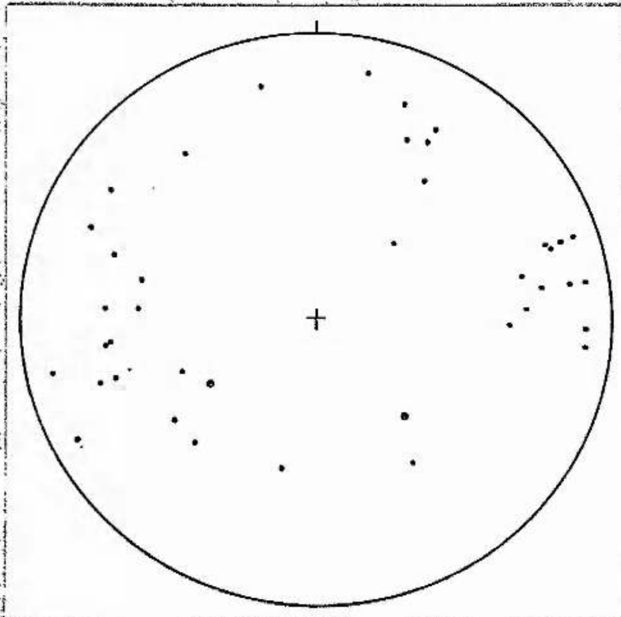


Fig. XVIII-61

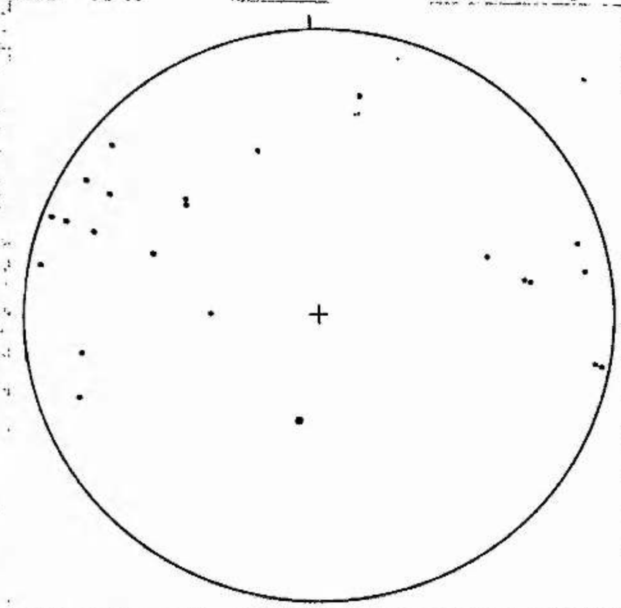


Fig. XVIII-62

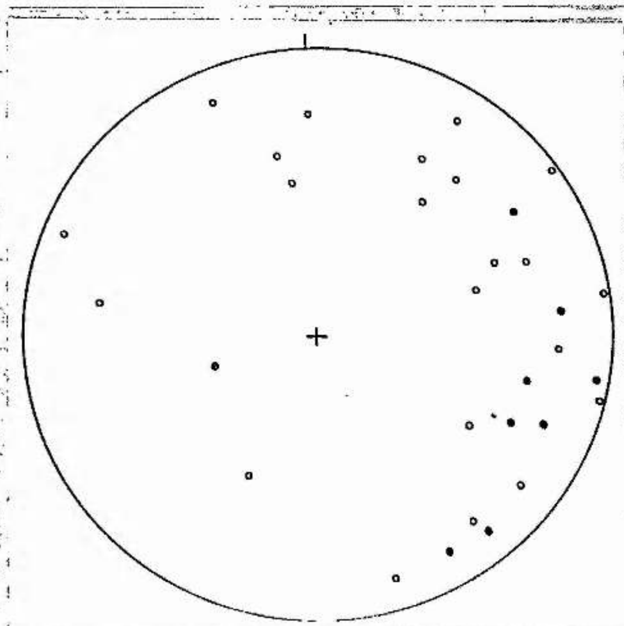


Fig. XVIII-63

Fig. XVIII-64. Synoptic diagram of approximate averages of groups of folds from all plots in true orientation.

Fig. XVIII-65. Composite diagram of the attitudes of 416 fold axes from all plots in relation to the average attitude of the foliation on Barra (pole represented by circled dot). Maxima plunge at 15° towards 55°, (20° towards 86°), 20° towards 110° and 10° towards 142°. Contours at 1%, 5%, 7.5% and 10% intervals.

Fig. XVIII-66. Synoptic diagram of approximate averages of groups of folds, other than those with east-south-east and south-east trends, in relation to the average foliation attitude for Barra (circled dot represents the pole). Solid circle represents strong concentration.

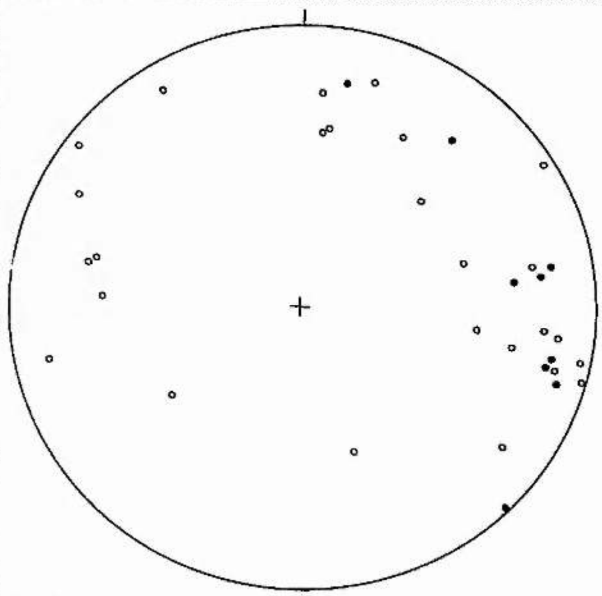


Fig. XVIII-64

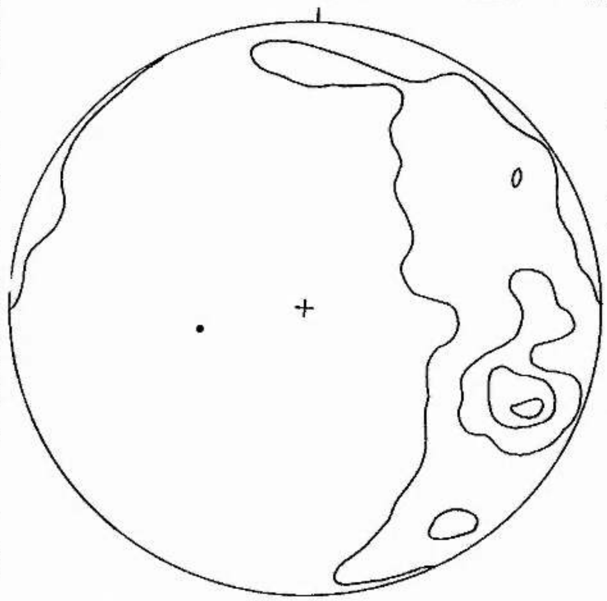


Fig. XVIII-65

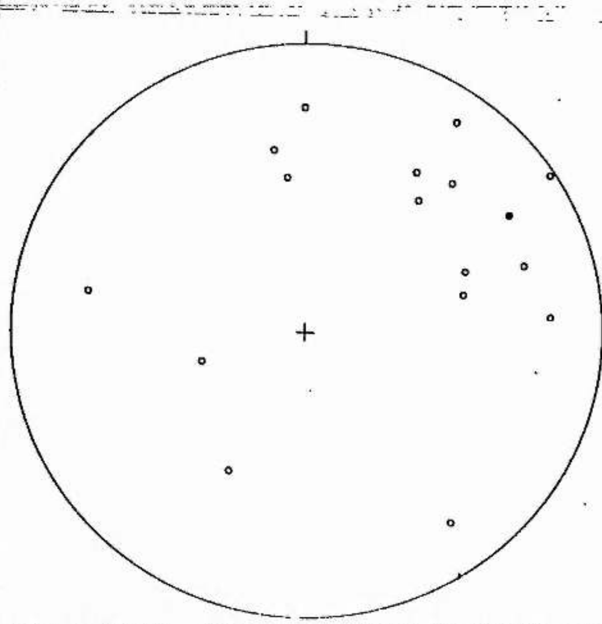


Fig. XVIII-66

Fig. XVIII-67. Equal area plot of all folds axes (154) other than those trending east-south-east and south-east in relation to the attitude of the average foliation for Barra (circled dot represents the pole). Contours at 2.5%, 5% and 10% intervals.

Fig. XVIII-68. Synoptic diagram of approximate maxima of fold axial groups in their true orientation showing the trends of any tendency towards elongation of the groups. Solid circles represent strong concentrations and open circles diffuse groups. Sections of small circles about F_4 are dashed and those about F_5 dotted and dashed.

Fig. XVIII-69. Composite equal area plot of the plunges of all (416) small fold axes from all plots in their true orientations. Maxima plunge at 10° towards 12°, 20° towards 82° and 12° towards 104°. Contours at 1%, 2.5%, 5%, 7.5% and 10% intervals. Average foliation attitude shown by dashed line.

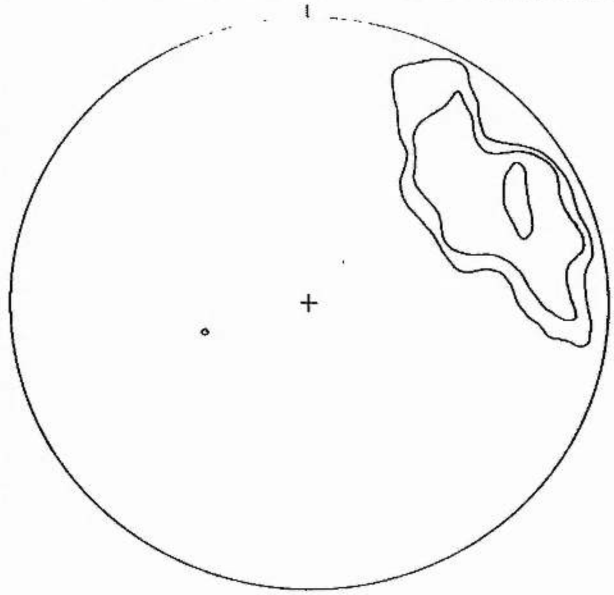


Fig. XVIII-67

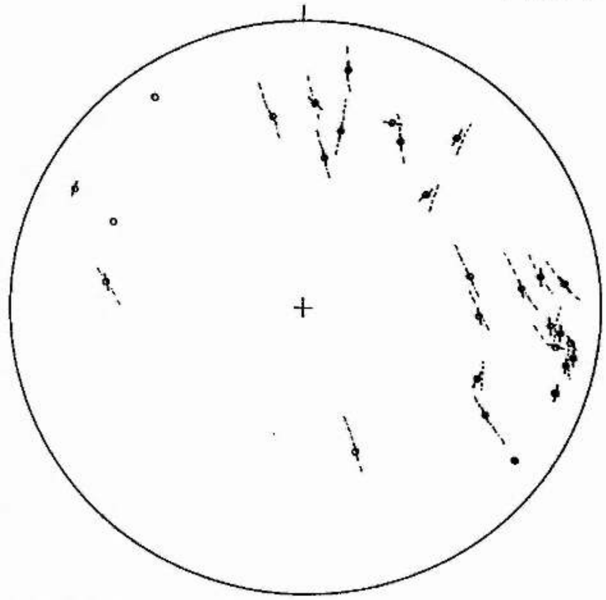


Fig. XVIII-68

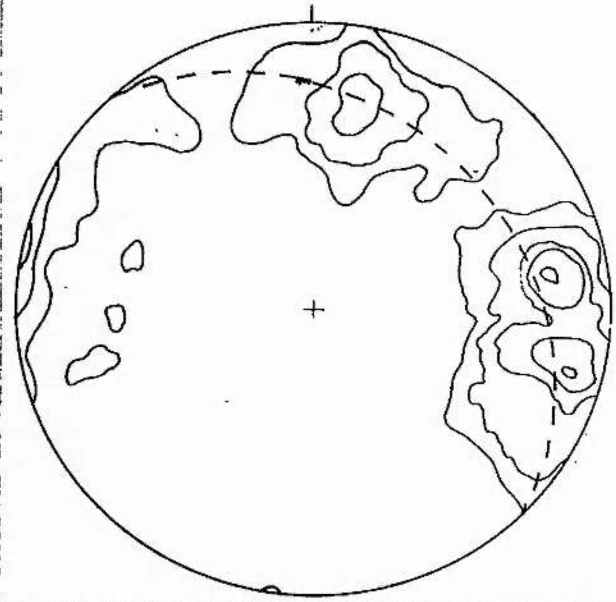


Fig. XVIII-69

Fig. XVIII-70. Composite equal area plot of all (271) small fold axial plunges from localities having approximately the same foliation orientation (dashed line). Maxima plunge at approximately 25° towards 10°, 46° towards 84° and 12° towards 102°. Contours at 1%, 2.5%, 5%, 7.5%, 10% and 12.5% intervals.

Fig. XVIII-71. The group of north-east plunging fold axes of figure XVIII-70 after levelling of the F_4 axis about F_5.

Fig. XVIII-72. β-diagram of the foliation from the three exposures I, II, III south of Bagh nan Clach, β- maxima plunge at 35° towards 22°, 30° towards 60°, 20° towards 80°, 5° towards 120° and 35° towards 160°. 310 points. Contours at 2.5%, 5% and 7.5% intervals.

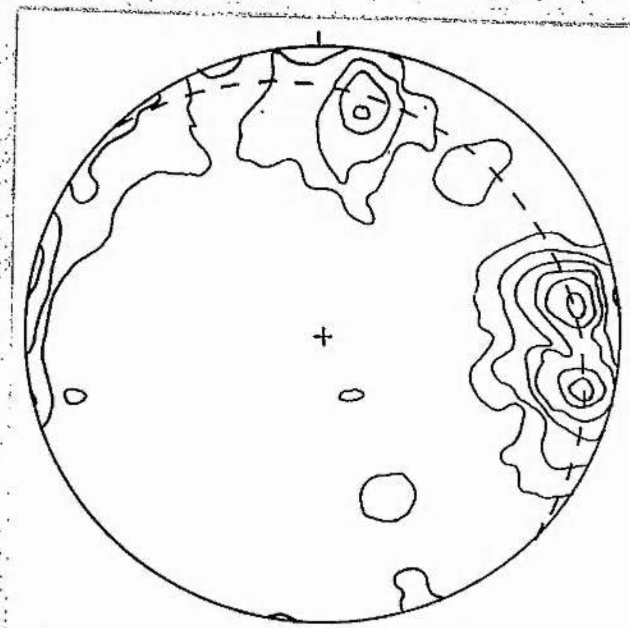


Fig. XVIII-70

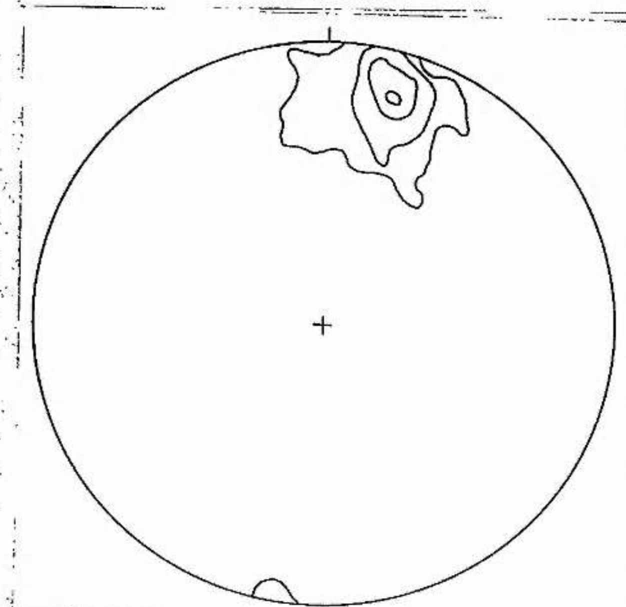


Fig. XVIII-71

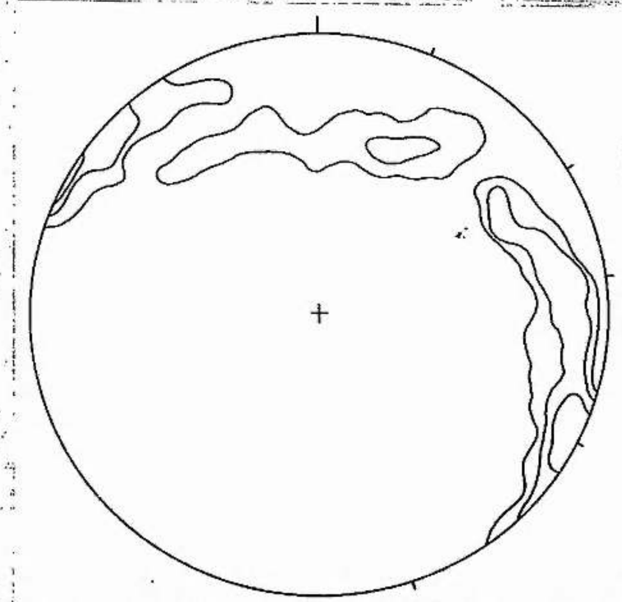


Fig. XVIII-72

Fig. XVIII-73. Plot of the strikes of all steep and vertical joints measured from aerial photographs.

Fig. XVIII-74. Plot of the strikes of all steep and vertical joints measured from aerial photographs. East of the Heaval Thrust.

Fig. XVIII-75. Plot of the strikes of all steep and vertical joints measured from aerial photographs. West of the Heaval Thrust.

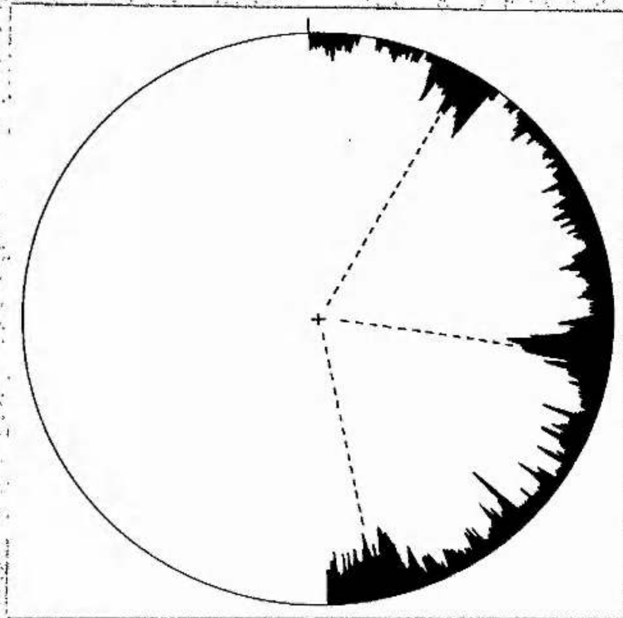


Fig. XVIII-73

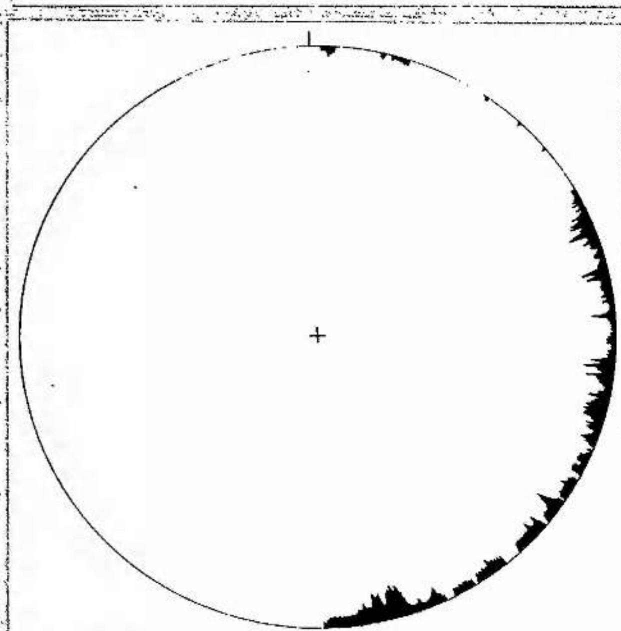


Fig. XVIII-74

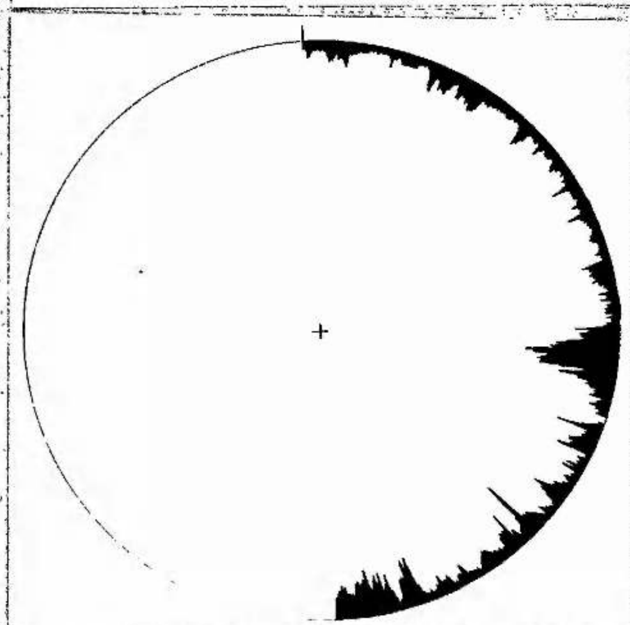


Fig. XVIII-75

Fig. XVIII-76. Hypothetical form of a perfectly developed pattern of steep and vertical joints related to thrusting from the east (solid lines), compared with that related to the probable direction stresses responsible for F_2 folding (dashed lines).

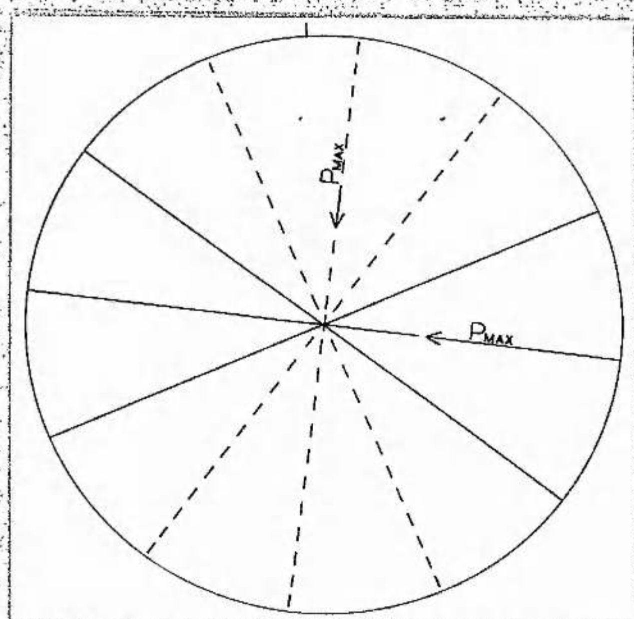


Fig. XVIII-76

Fig. XIX-1. Composite 10 feet wide quartz (white centre) and feldspar (grey margins) pegmatite vein striking 50°. The irregular margin of the quartz centre suggests later emplacement into a pink feldspathic vein. Note Lewisian dyke cut by the vein (right foreground) without change in orientation. The pegmatite vein can be seen to stop abruptly in the middle background where it is cut by the Phase 7c granulite dyke of figures X-5 and XIX-2.

Fig. XIX-2. Thin quartzo-feldspathic pegmatite veins in a granulite dyke showing characteristic darkened margins due to migmatisation. The width of the margins in which the garnets are much larger than in the rest of the granulite is greater than that of the veins and suggests that the dyke was in a region of strong anatexis when the vein was injected. East Leenish.

Fig. XIX-3. Homogeneous, 8 feet wide quartzo-feldspathic pegmatite vein cutting pyroxenic basic country rock at Leenish.

Fig. XIX-1

Fig. XIX-2

Fig. XIX-3

Fig. XIX-4. Ptygmatic quartzo-feldspathic folds. Bagh nan Clach.

Fig. XIX-5. Small rotation boudins formed in a thin quartzo-feldspathic vein. Bagh nan Clach.

Fig. XIX-6. Diagram to show the orientation of the shear surfaces responsible for the structures of Figure XVIII-5.

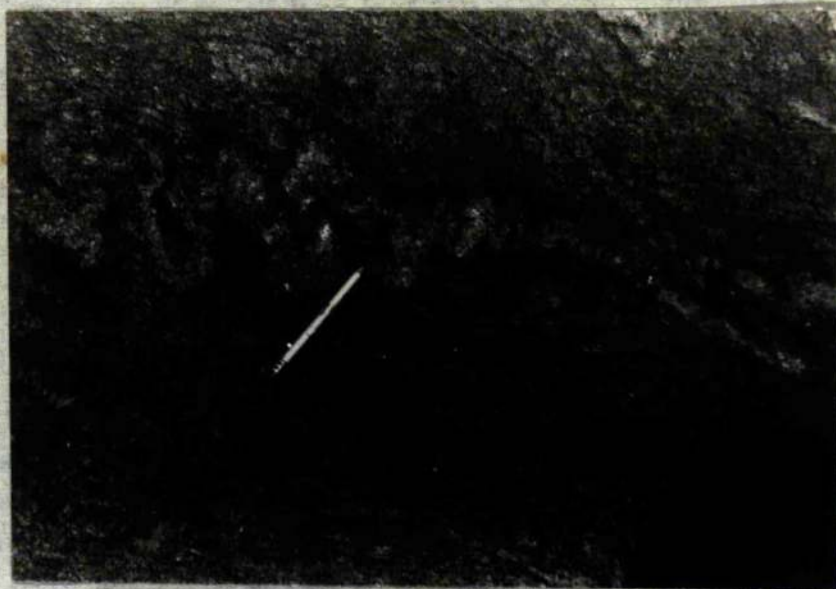


Fig. XIX-4

Fig. XIX-5

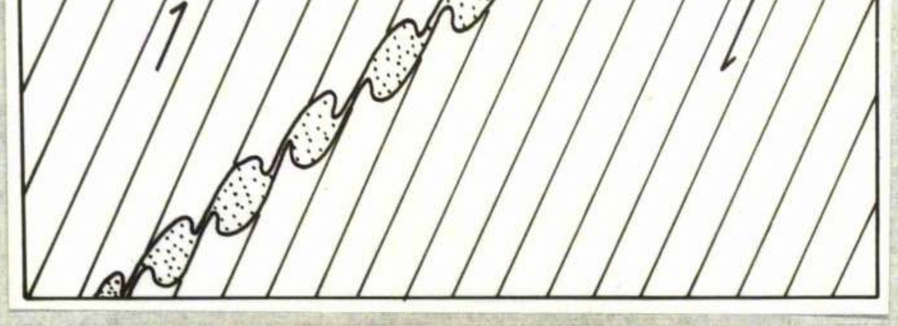


Fig. XIX-6

Fig. XIX-7. Photograph of a ptygmatic style of fold formed by shear. Boulder from Bagh nan Clach. Slab is 8 inches long. Note increase in intensity and amplitude of folding nearer the shear surface at top left.

Fig. XIX-8. Remnant of an isoclinally folded amphibolite in migmatite in an advanced state of anatexis. Scurrival.

Fig. XIX-9. Attack of basic gneiss by migmatizing front which moved in a direction towards the camera. North of Allt Heiker.

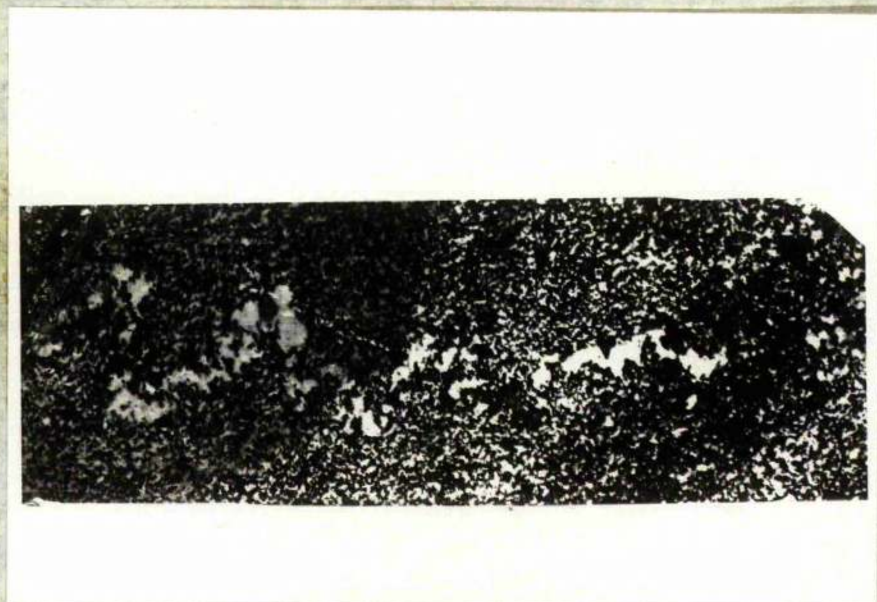


Fig. XIX-7

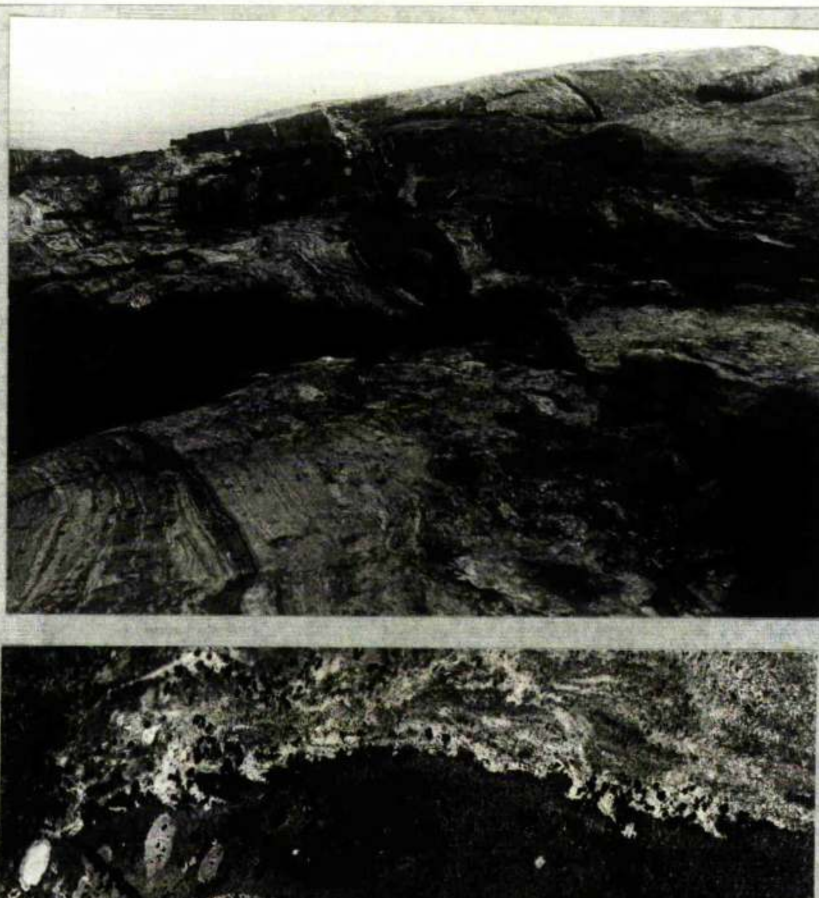


Fig. XIX-8

Fig. XIX-9

Fig. XIX-10. Interfingering migmatite penetrating amphibolite parallel to the foliation. Dark rims in the basic gneiss adjacent to the migmatite can be seen at the top left and the migmatite nearest the amphibolite under the pencil is darker grey in colour. Rudha Mhor.

Fig. XIX-11. Anatexis of amphibolite. Mould-like pattern of branching fingers of migmatite "frozen" in the act of gradually reducing the size of the large mass of basic gneiss to form an agmatite. South-east coast.

Fig. XIX-12. Incipient anatexis of basic gneiss. Small tongues and patches of quartzo-feldspathic migmatite penetrating the gneiss at an early stage in the formation of agmatite. Halaman Bay.

Fig. XIX-10

Fig. XIX-11

Fig. XIX-12

Fig. XIX-13. Basic agmatite crossed by 100° lineation (parallel to the pencil). The 60° trending quartzo-feldspathic pegmatite vein across the back of the figure is wrinkled by 100° type folds. Lineation cuts the thin vein below the pencil point. Relict foliation in the blocks indicates that rotation of these has taken place after brecciation. Evidence for attack of the blocks is seen in the quartzo-feldspathic rims surrounding them. South side of Bruernish peninsula.

Fig. XIX-14. Anatexis from above, of a basic band (lower part of figure) containing early remnants of a basic dyke in the centre surrounded by a quartzo-feldspathic rim. The dark knot is clearly more resistant to attack by migma than the gneiss of the lower part of the picture. South-east coast.

Fig. XIX-15. Agmatite in which the blocks still preserve their individuality but show evidence of migmatization. Even thin basic dykes have been broken up by the migma and survive only inside the blocks of intermediate gneiss. Rudha Mor.

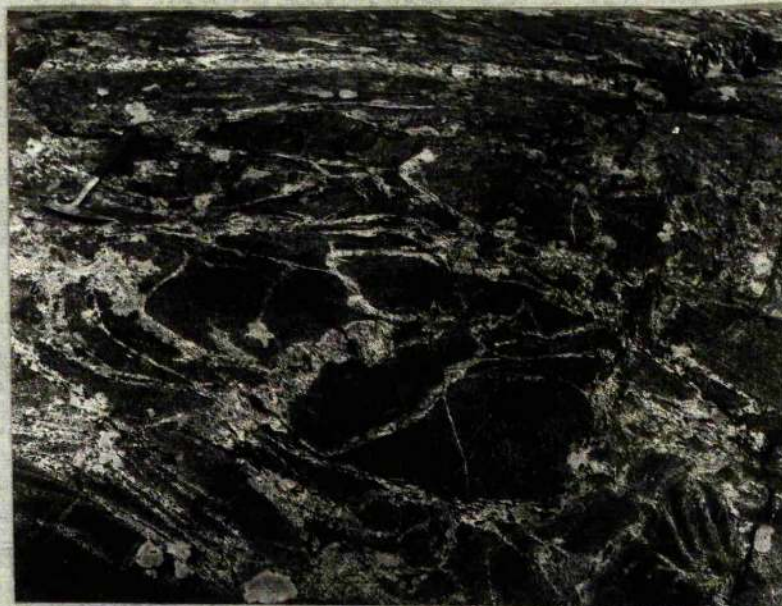


Fig. XIX-13

Fig. XIX-14

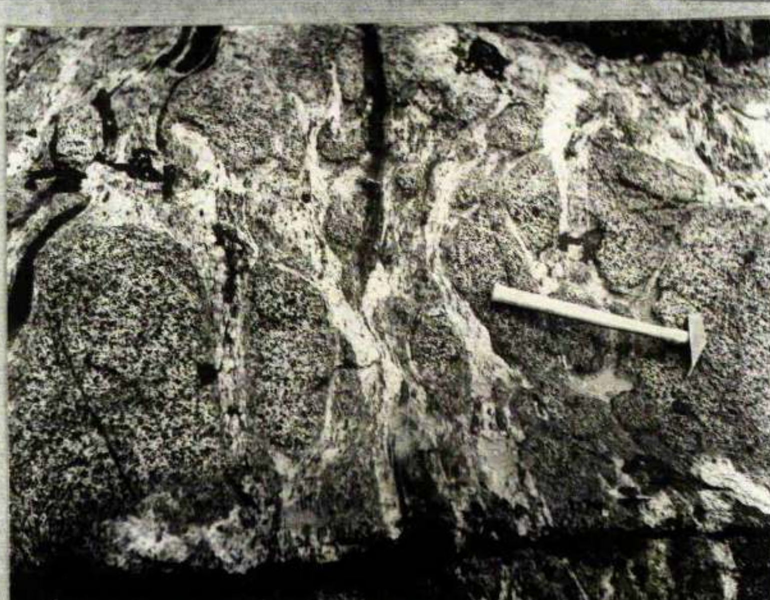


Fig. XIX-15

Fig. XIX-16. Basic agmatite in which the original amphibolite band is almost completely "digested". A later grey intermediate to basic dyke on the left has invaded the agmatite and has been itself slightly attacked by later anatexis. South-east coast.

Fig. XIX-17. Coarse massive basic pegmatite invaded by a feldspathic vein. Ersary.

Fig. XIX-18. Lewisian dyke in anatexite. The dyke, although breached by the migma, still preserves its sheet-like form and presents sharp boundaries to the surrounding massive quartzo-feldspathic gneiss. South-east Bruernish.

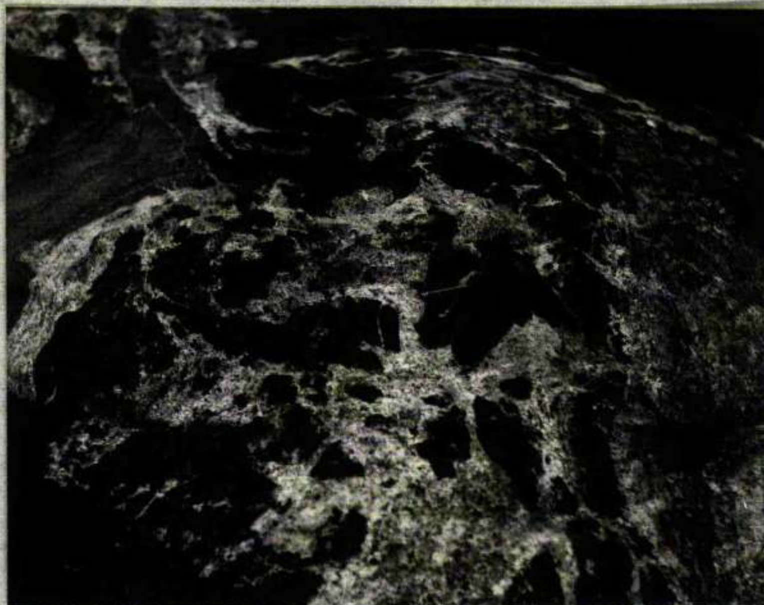


Fig. XIX-16

Fig. XIX-17

Fig. XIX-18

Fig. XIX-19. Thin relict folded amphibolite bands in almost homogeneous migmatite. The apparent angular discordance on the left is probably due to relict banding on the limb of an isoclinal synform closing at the bottom left hand corner of the photograph. West coast of Fiary.

Fig. XIX-20. Evidence of disharmonic folding preserved in almost homogeneous quartzo-feldspathic gneiss by the relict amphibolite layer which has survived anatexis almost entirely. Shore on the west side of Fiary.

Fig. XIX-21. Extreme anatexis of basic gneiss transformed to masses of coarse hornblende and garnet crystals in pink feld-spar. Leenish.

Fig. XIX-19

Fig. XIX-20

Fig. XIX-21

Fig. XIX-22. Anatexis of an amphibolite band. The migmatizing front has moved obliquely towards the top of the picture, affecting the lower part of the band more than the upper. The thin band at the top left does not appear to have been affected at all. Shore at Eoligarry.

Fig. XIX-23. Diagram to show the postulated direction of movement of the migmatizing front (upwards from right to left in the figure) through the basic gneiss of figure 22.

Fig. XIX-24. Migmatizing front arrested at a 10 inch dyke cutting foliated quartzo-feldspathic and intermediate gneisses. The dyke (the diagonal grey band under the pencil) presents a lobate boundary to the migma which has stoped off small curved fragments (above pencil). To the right the remnants of the basic gneiss fade interceptibly into the migmatite in which very faint relict banding can still be seen standing perpendicular to the dyke. To the left of the pencil the migmatizing front has broken through below the dyke. The whole has been cut by a late thin quartzo-feldspathic vein. The black spots are oil splashes on the rock. Shore north-east of Ersary.

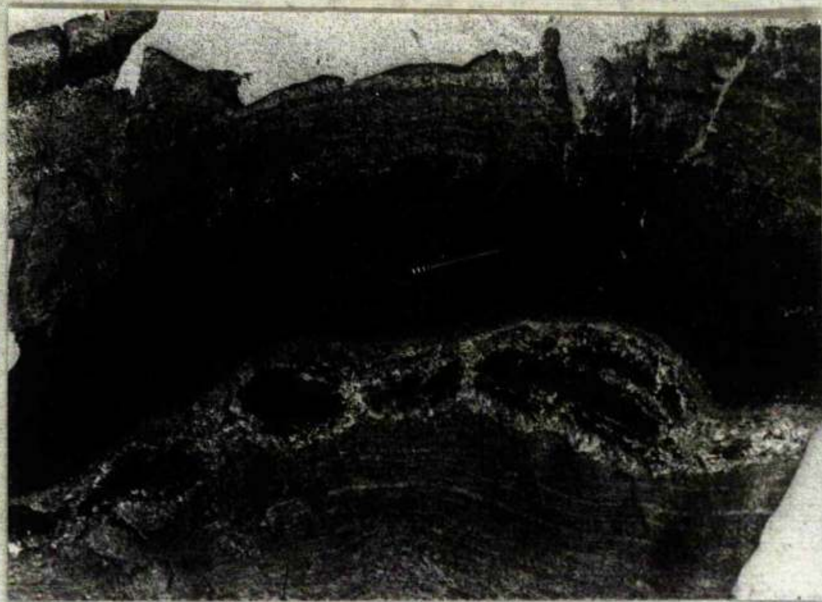


Fig. XIX-22

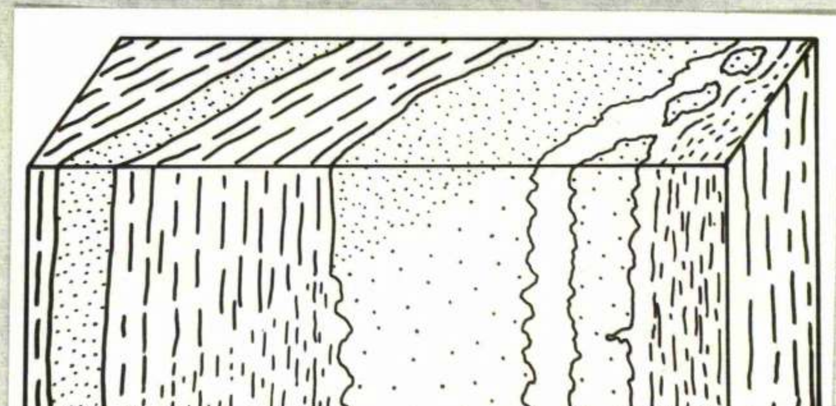


Fig. XIX-23

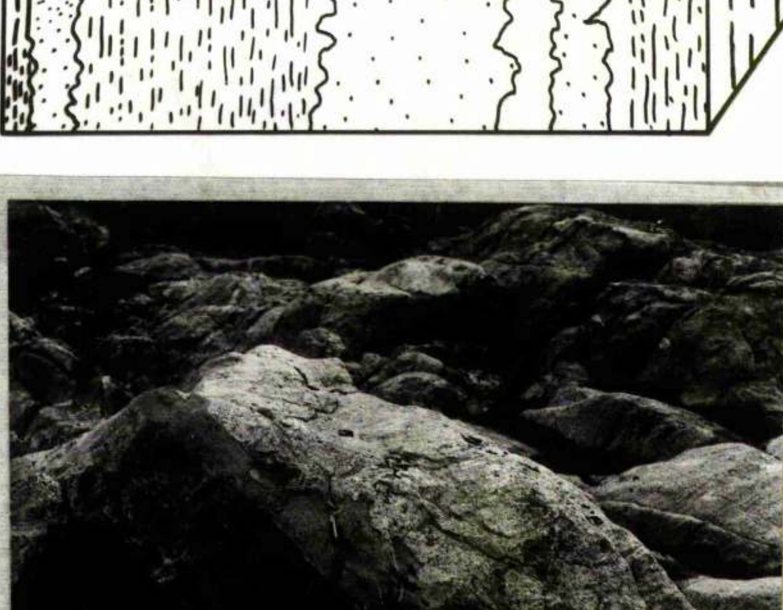


Fig. XIX-24

Fig. XIX-25. Tectonic inclusions ("fish") in massive migmatite derived from foliated quartzo-feldspathic gneiss. Shore north of Ersary a few yards from the location of Figure 25.

Fig. XIX-26. Block of amphibolite in migmatite. Despite the sharp boundaries, attack has proceeded at small isolated centres parallel to the fine s-surfaces defined by amphibole alignment. Relict banding is still present although the block has clearly moved away from its neighbours through the migma. Bruernish.

Fig. XIX-27. Migmatized amphibolite band in which anatexis has advanced equally on both sides. This shows the characteristic interfingering of the quartzo-feldspathic tongues and the darkening of the margins of the basic fragments and gradual fading of the banding in the adjacent intermediate foliated gneisses. Head of Borve valley.

Fig. XIX-25

Fig. XIX-26

Fig. XIX-27

Fig. XIX-28. Migmatite showing the relative effects of anatexis on basic, intermediate and acid bands. Thin folded basic bands remain floating in migma after the intermediate gneiss has been "digested". The same effect can be seen in the sharp margin on the basic side of the thick band under the pencil and the gradational contact on the acid side. Rudha Mor.

Fig. XIX-29. Migmatite containing patches of hornblende with biotite rims representing fragments of an early basic band (probably a dyke). Folds of F_2 style with axial surface trend parallel to the pencil. Shore north of pier, Eoligarry.

Fig. XIX-30. Thin quartzo-feldspathic vein cutting a granulite dyke. The dyke adjacent to the vein has been only slightly affected as can be seen by the thin dark border on one side of the vein beneath the pencil. Rudha Liath.

Fig. XIX-28

Fig. XIX-29

Fig. XIX-30

Fig. XIX-31. Gradation from quartzo-feldspathic migmatitic gneiss (top), faintly foliated parallel to the hammer handle, to unfoliated pegmatite in the foreground. West end of Ard Greian.

Fig. XIX-32. Remnants of foliated quartzo-feldspathic gneiss preserved as a pillar in a small region of almost complete local anatexis. The recrystallized anatexite has not altered the orientation of the banded remnant in which the foliation is still parallel to that of the adjacent gneiss. West side of Ben Scurrival.

Fig. XIX-33. Remnant of foliated intermediate gneiss which has drifted from its original relative position (banding is at a high angle to that of the adjacent gneiss) in an anatexite. The comparatively sharp edges of the fragment compared with that of Figure 32 suggest that migmatization was not sufficiently intense to attack the xenolith. West of Loch Obe.

Fig. XIX-31

Fig. XIX-32

Fig. XIX-33

Fig. XIX-34. Migmatization and flow along the axial surface of a monoclinic fold. Anatexis (followed by recrystallization) of some of the quartzo-feldspathic layers appears to have provided the material which has flowed into the axial surface of the fold. Shore east of Eoligarry.

Fig. XIX-35. Plot of the strikes of rectilinear quartzo-feldspathic pegmatite bodies. Barra.

Fig. XIX-36. Intrafolial fold of amphibolite in banded quartzo-feldspathic gneiss. West coast of Fiary.

Fig. XIX-34

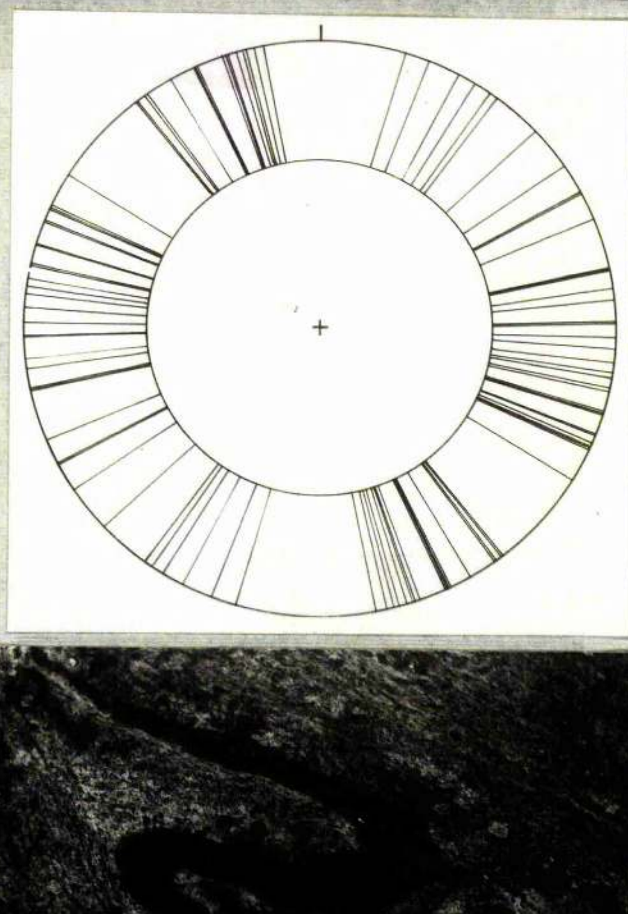
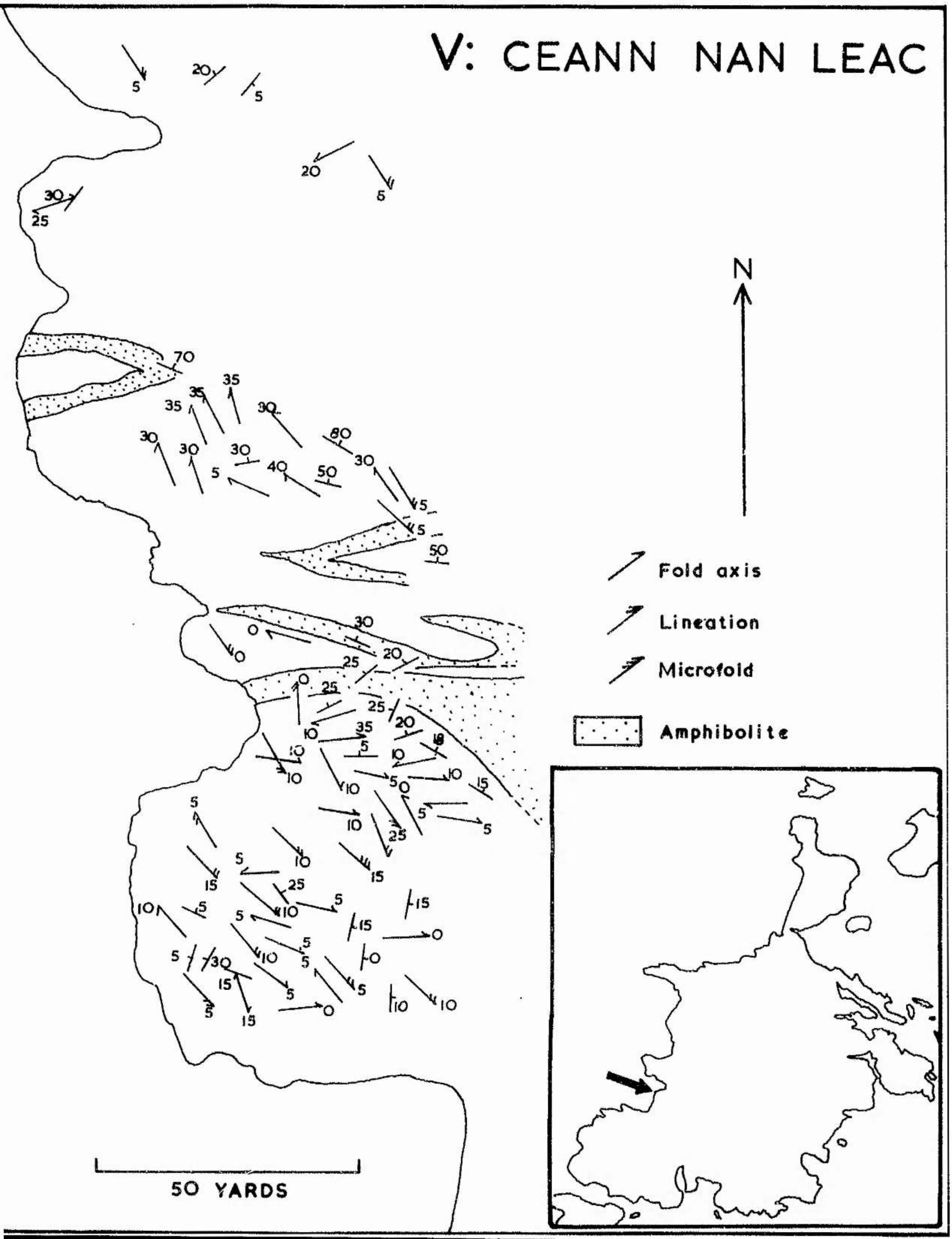
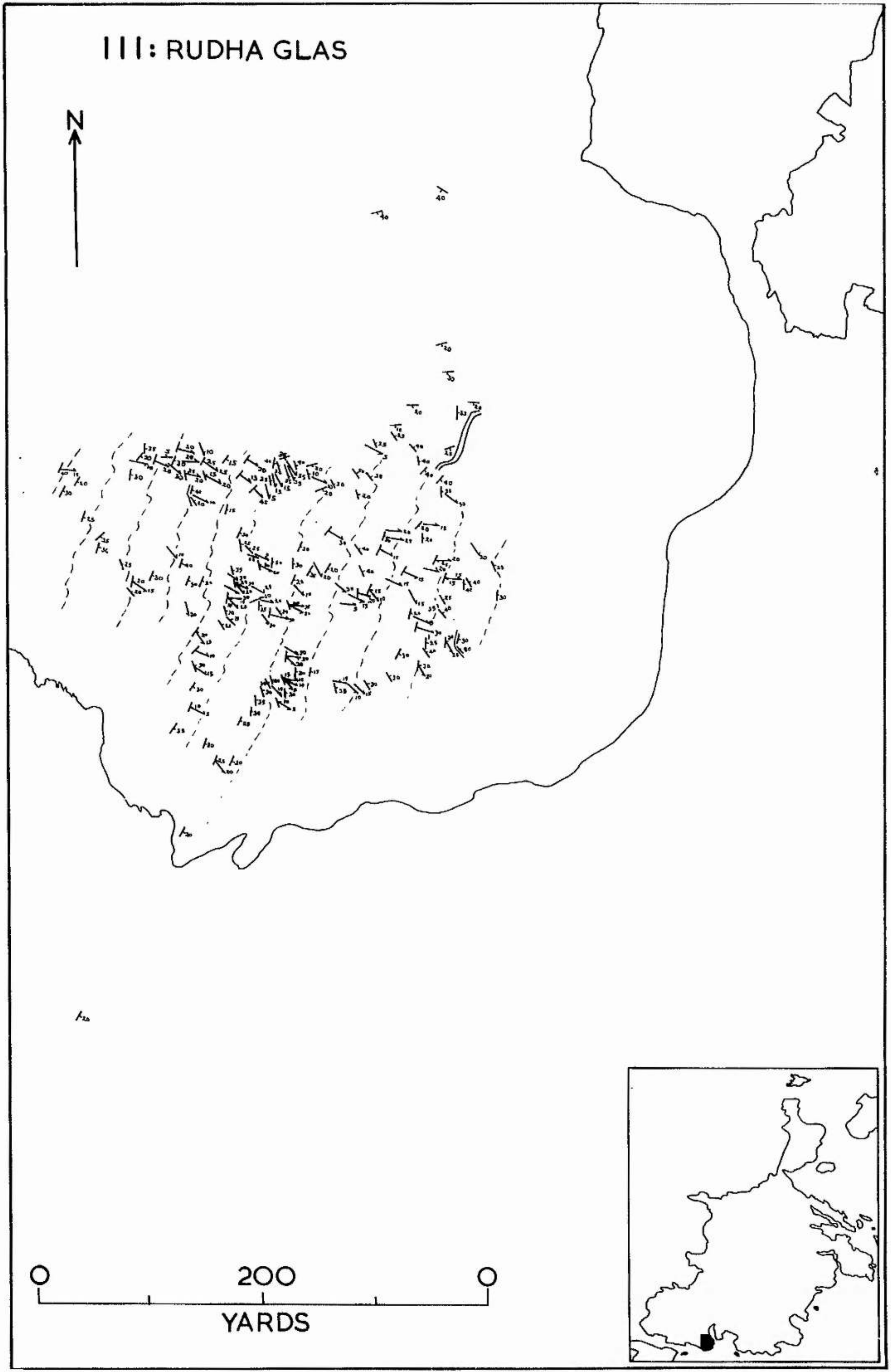
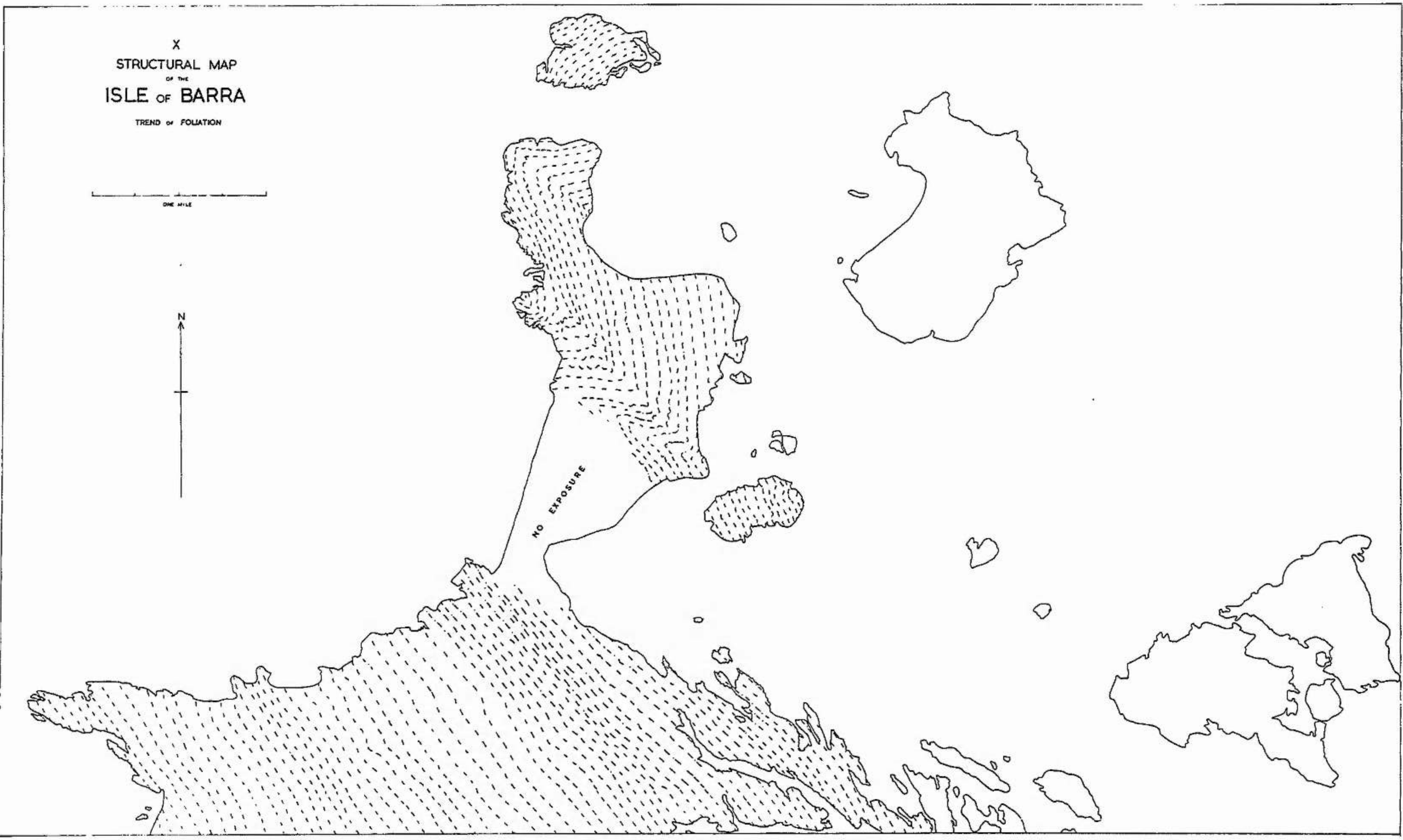


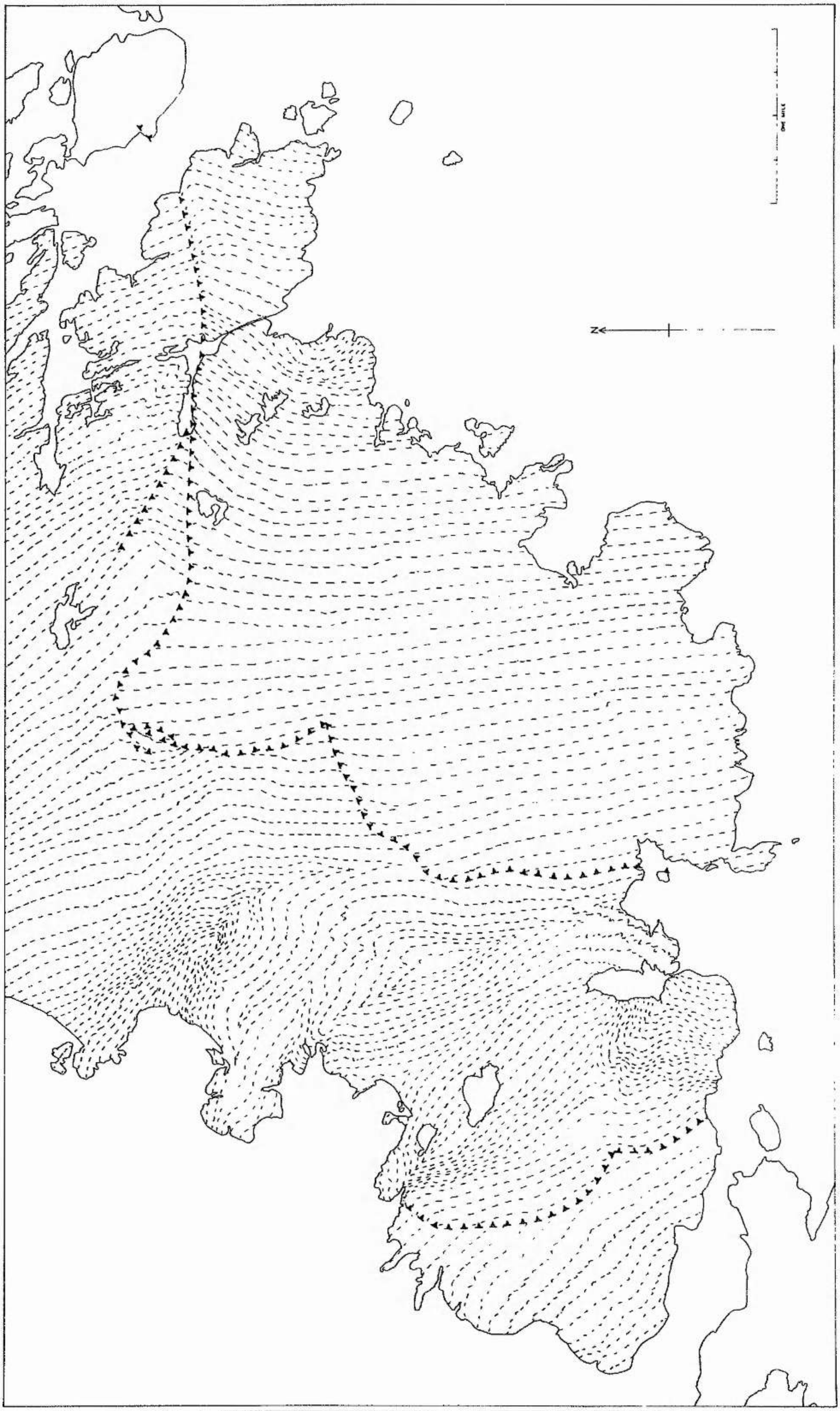
Fig. XIX-35

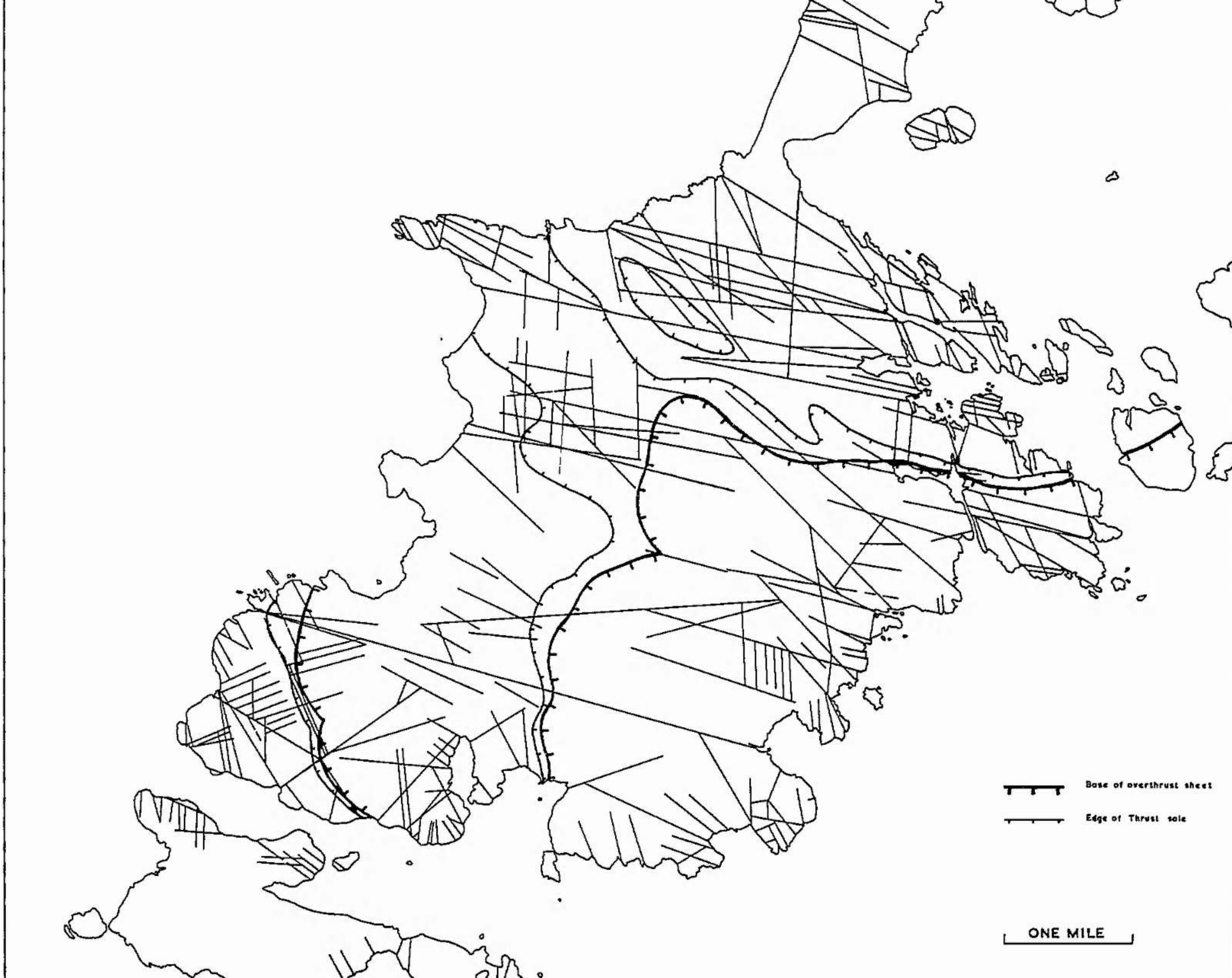
Fig. XIX-36

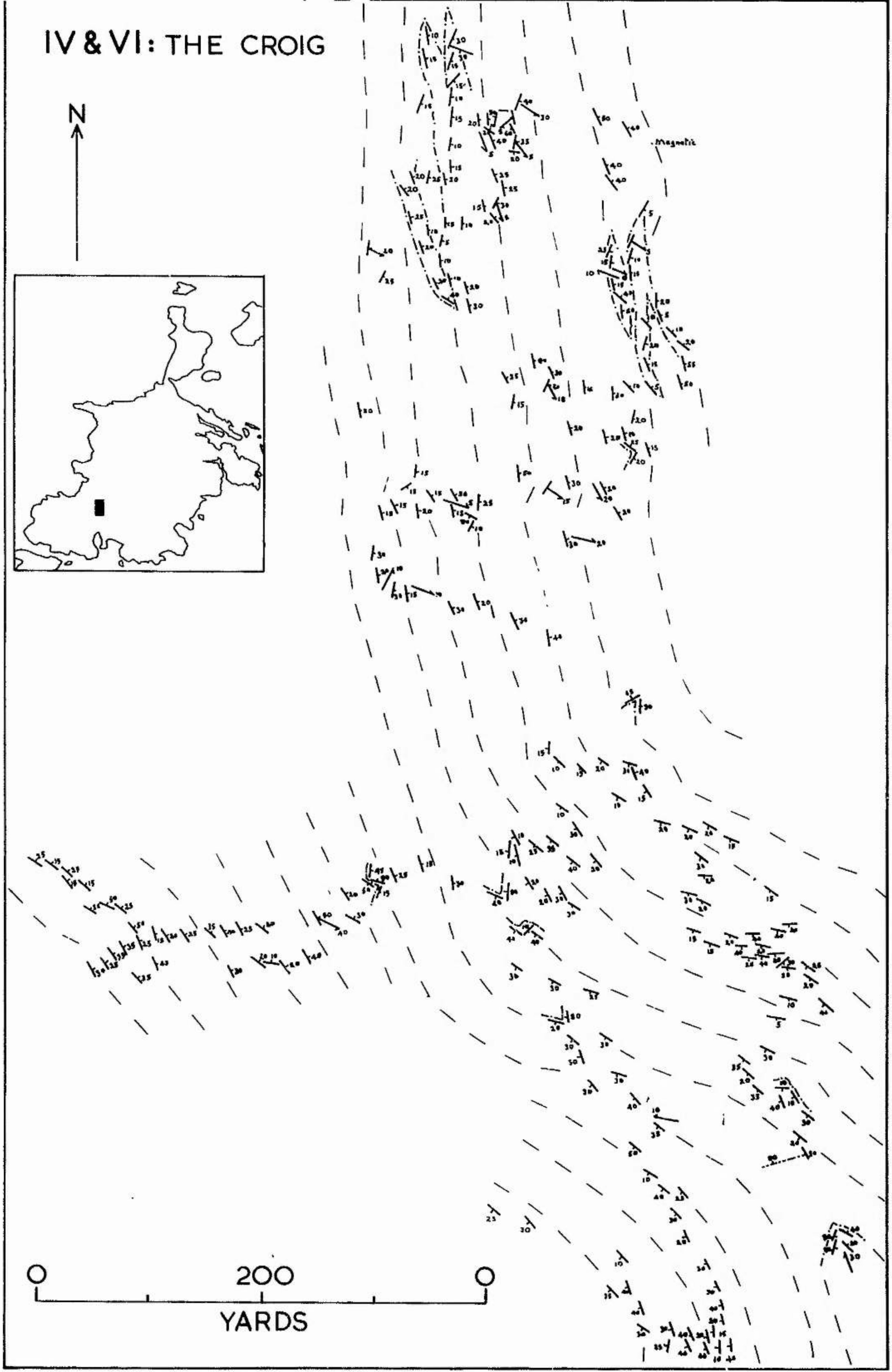

V: CEANN NAN LEAC
N
Fold axis
Lineation
Microfold
Amphibolite
50 YARDS


III: RUDHA GLAS
N
0
200
0
YARDS


X
STRUCTURAL MAP
OF THE
ISLE OF BARRA
TREND OF FOLIATION
ONE MILE
N
NO EXPOSURE


N
ONE MILE


Base of overthrust sheet
Edge of Thrust sole
ONE MILE



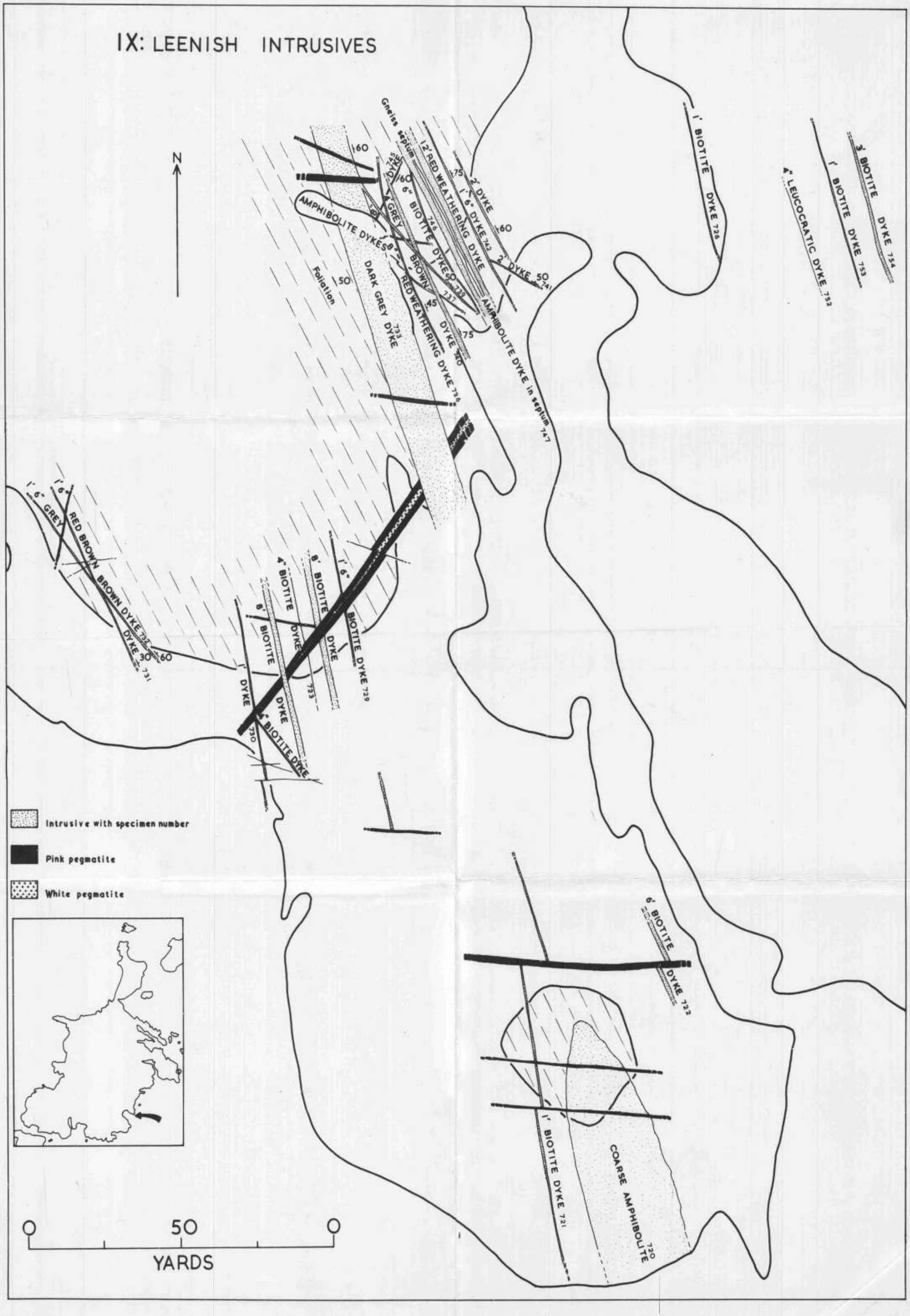
IV & VI: THE CROIG
N
Magnetic
0
200
0
YARDS

Fig. XIX-28

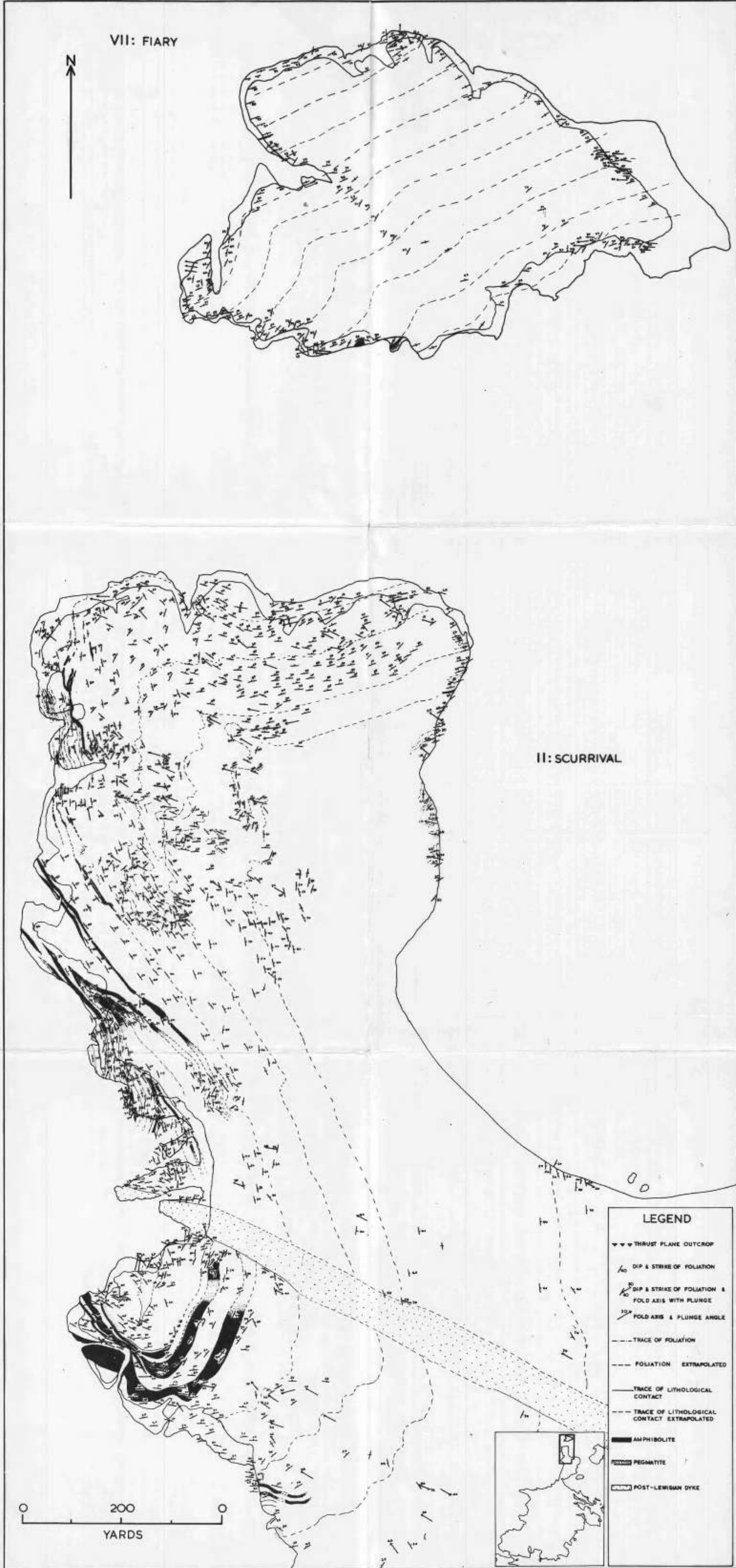
Fig. XIX-29

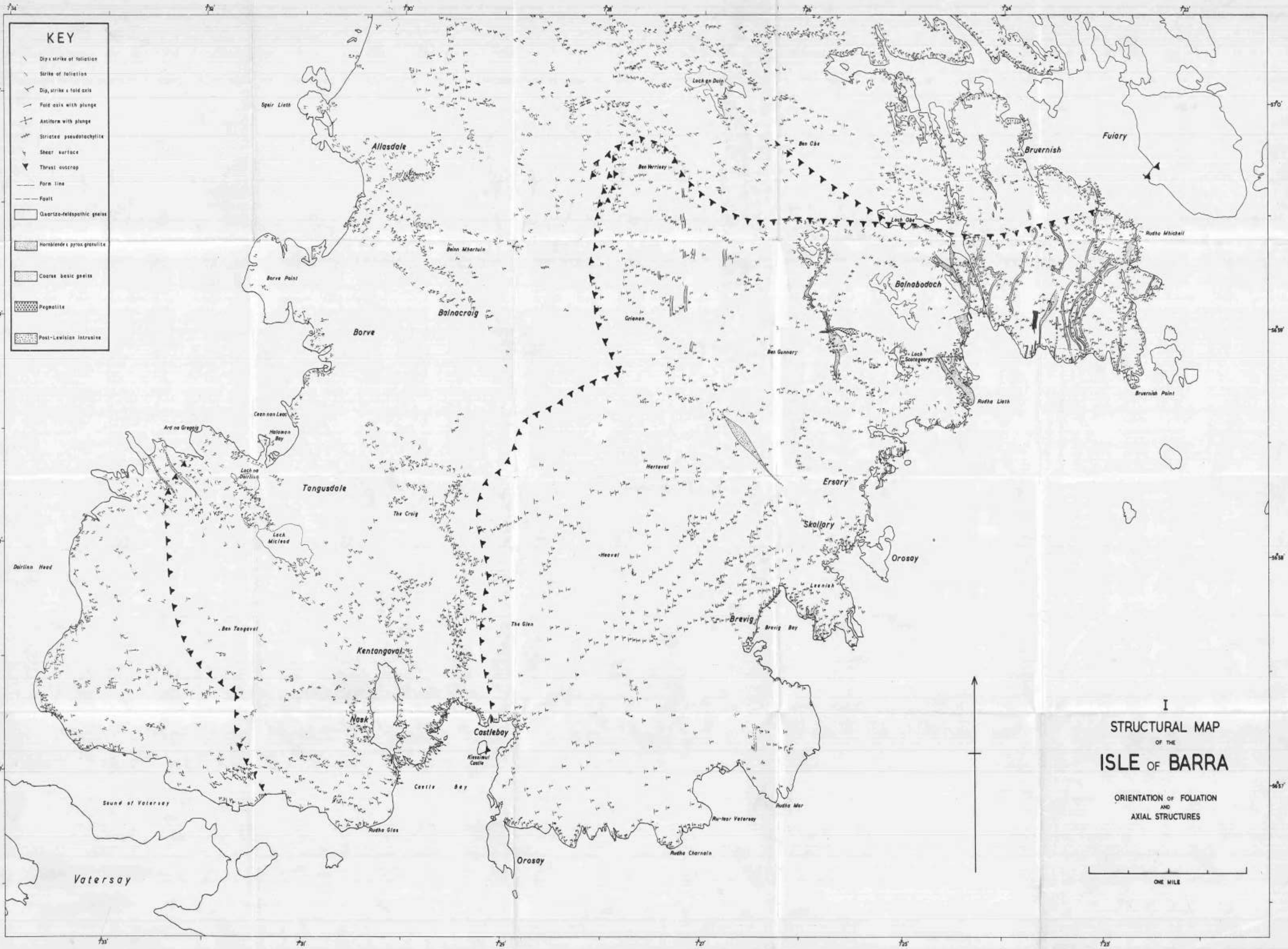
Fig. XIX-30


I
STRUCTURAL MAP
OF THE
ISLE OF BARRA
ORIENTATION OF FOLIATION
AND
AXIAL STRUCTURES
ONE MILE
N
KEY
Dips strike of foliation
Strike of foliation
Dip, strike & fold axis
Fold axis with plunge
Antiform with plunge
Striated pseudotachylite
Shear surface
Thrust outcrop
Form line
Fault
Quartzo-feldspathic gneiss
Coarse basic gneiss
Pegmatite
Post-Lewisian intrusive
Fiary
Scurrival Point
Scurrival
Ben Scurrival
Fuday
Bogh nan Cloch
Eoligarry
Pier
Ben Eoligarry Mor
Orosay
Traigh Mhor
Gighay
Vaslain
Ardvuran
Greian Head
Cliad
Ben Cliad
Greian
Cuier
Ard Mhor
Ard Veenish
Hellisay



IX: LEENISH INTRUSIVES
N
Gneiss septum
12' RED WEATHERING DYKE
6" BIOTITE DYKE
AMPHIBOLITE DYKES
GREY
BROWN
RED WEATHERING DYKE 736
DARK GREY DYKE 733
Foliation
AMPHIBOLITE DYKE in septum 747
2' DYKE
2' DYKE 741
1' BIOTITE DYKE 726
4" LEUCOCRATIC DYKE 752
1' BIOTITE DYKE 753
3' BIOTITE DYKE 754
1' 6" GREY
1' 6" RED BROWN
BROWN DYKE 732
DYKE 731
4" BIOTITE DYKE 723
8' BIOTITE DYKE
1' 6" BIOTITE DYKE 729
8' BIOTITE
1' DYKE 730
4" BIOTITE DYKE
6' BIOTITE DYKE 722
1' BIOTITE DYKE 721
COARSE AMPHIBOLITE 720
Intrusive with specimen number
Pink pegmatite
White pegmatite
0
50
0
YARDS


VII: FIARY
N
II: SCURRIVAL
LEGEND
THRUST PLANE OUTCROP
DIP & STRIKE OF FOLIATION
DIP & STRIKE OF FOLIATION & FOLD AXIS WITH PLUNGE
FOLD AXIS & PLUNGE ANGLE
TRACE OF FOLIATION
FOLIATION EXTRAPOLATED
TRACE OF LITHOLOGICAL CONTACT
TRACE OF LITHOLOGICAL CONTACT EXTRAPOLATED
AMPHIBOLITE
PEGMATITE
POST-LEWISIAN DYKE
0
200
0
YARDS


KEY
Dip & strike of foliation
Strike of foliation
Dip, strike & fold axis
Fold axis with plunge
Antiform with plunge
Striated pseudotachylite
Shear surface
Thrust outcrop
Form line
Fault
Quartzo-feldspathic gneiss
Hornblende & pyrox. granulite
Coarse basic gneiss
Pegmatite
Post-Lewisian intrusive
I
STRUCTURAL MAP
OF THE
ISLE OF BARRA
ORIENTATION OF FOLIATION
AND
AXIAL STRUCTURES
ONE MILE
Allasdale
Borve
Balnacraig
Tangusdale
Kentangaval
Nask
Castlebay
Kisimul Castle
Castle Bay
Vatersay
Sound of Vatersay
Orosay
Brevig
Brevig Bay
Skallary
Ersary
Balnabodach
Bruernish
Fuiary
Bruernish Point
Rudha Mhicheil
Rudha Liath
Loch Obe
Ben Obe
Ben Verrisey
Grianan
Ben Gunnary
Heaval
Hartaval
The Glen
The Craig
Ben Tangaval
Dorlinn Head
Ard na Greine
Halaman Bay
Loch nan Eilean
Borve Point
Sgeir Liath
Loch an Duin
Beinn Mhartuin
Rudha Glas
Rudha Charnain
Rudha Mor
Leenish
Loch Mic'leod
Ru-tear Vatersay